Adaptation Pathways for Direct Air Capture Deployment in Canada

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Systems Design Engineering

Waterloo, Ontario, Canada, 2025

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This thesis is partially the product of collaborative research, and co-authored publications as follows:

Chapter 2:

- **Motlaghzadeh, K**., Schweizer, V., Craik, N., & Moreno-Cruz, J. (2023). Key uncertainties behind global projections of direct air capture deployment. *Applied energy*, *348*, 121485.

Chapter 2 of this thesis is a published paper (see the citation above) and is licensed under the Creative Commons Attribution–NonCommercial 4.0 (CC BY-NC 4.0) International License, which allows it to be used in this thesis. The paper is co-authored by myself, my supervisor Dr. Vanessa Schweizer (VS), Dr. Neil Craik (NC), and Dr. Juan Moreno-Cruz (JM). I served as the first and corresponding author, taking primary responsibility for the design, analysis, and writing of the paper. VS, NC, and JM provided supervision, contributed to the conceptual framing and methodology, and assisted with editing and validation of the analysis.

Chapter 3:

- **Motlaghzadeh, K**., Craik, N., Moreno-Cruz, J., Schweizer, V., Fuhrman, J., & Hipel, K. W. (2025). Applying equity principles leads to higher carbon removal obligations in Canada. *Communications Earth & Environment*, *6*(1), 88.

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Chapter 4:

- **Motlaghzadeh, K**., & Schweizer, V. (Under review). *Future of DAC in Canada: A scenario-based exploration of barriers and possibilities*. Under review at *Energy Research & Social Science.*

Chapter 4 of this thesis has been incorporated into a paper which is under review at the journal *Energy Research & Social Science*. This paper was co-authored by myself and my supervisor, Dr. Vanessa Schweizer (VS). I prepared the initial draft, while VS supervised the work, provided revisions, and offered critical feedback.

Chapter 5:

- **Motlaghzadeh, K**., & Schweizer, V. (In preparation). *Adaptation Pathways for Direct Air Capture in Canada: A Proposed Framework for Multi-Sectoral Responses to Deep Techno-Economic and Socio-Political Uncertainty*. To be submitted at *npj Climate Action*

Chapter 5 of this thesis will be incorporated into a manuscript being prepared to submit to a call for papers entitled "Adaptation Pathways and Scenarios for Climate Change Research" with npj Climate Action.

Abstract

This study responds to the insufficient understanding of the uncertainties surrounding the demand, and the techno-economic and socio-political feasibility of deploying Direct Air Capture (DAC)—a Carbon Dioxide Removal (CDR) technology that may be essential for Canada's net-zero target and potential post-net-zero obligations. Limited tools are available to analyze such uncertainties and their interactions to support adaptive decision-making under deep uncertainty. These gaps are addressed through three interconnected, systems-based approaches: Integrated Assessment Modeling (IAM) for quantitative scenario modeling, Cross-Impact Balance (CIB) analysis for qualitative scenario discovery, and Adaptation Pathways (AP) for decision-support under deep uncertainty. First, existing IAM studies were systematically reviewed and a national-scale IAM analysis with the Global Change Analysis Model (GCAM) was conducted to quantify key uncertainties shaping DAC deployment in Canada. The following factors are found to strongly influence Canada's potential reliance on DAC: Socio-economic pathways, fossil-fuel dependence, international CDR obligations grounded in burden-sharing principles, and DAC cost trajectories. Second, the CIB scenario discovery method is employed to examine how these uncertainties—and additional socio-political factors not represented in quantitative models—interact based on expert elicitation with DAC specialists. The CIB analysis produces 15 internally consistent futures and identifies public acceptance and policy coherence as critical bottlenecks if they evolve unfavourably. Third, CIB scenarios are used to parameterize GCAM to quantify DAC demand under four internally consistent, CIB-informed futures. This integrated approach shows that Canada's DAC requirements could range from 0 to 300 $MtCO_2$/year by 2075, with narrative explanations linking each scenario's structural components to its resulting DAC trajectory. Finally, the AP framework is applied to DAC policy, mapping flexible and dynamic strategies across three key dimensions: economic feasibility, electricity supply, and CO_2 transport and storage. APs identify low-regret near-term actions (e.g., electricity grid expansion), reveal thresholds where strategies fail, and indicate when strategic shifts are needed. Methodologically, this thesis demonstrates (1) how semi-quantitative tools such as CIB can validate and enrich IAM scenarios with socio-political dynamics, and (2) how APs can translate uncertainty-rich futures into robust, actionable policy pathways for DAC deployment in Canada. Together, these methods provide a comprehensive decision-support framework for navigating the deep uncertainties surrounding DAC deployment in Canada.

Acknowledgements

I am deeply grateful to Professor Vanessa Schweizer, my supervisor and mentor, whose generosity, humility, and support have made my PhD journey both enriching and meaningful. She has been a constant source of encouragement, always giving her time generously and guiding me with patience and care. Her thoughtful supervision not only shaped the direction of my research and academic path but also inspired me to reflect on the kind of scholar, mentor, and—most importantly—human being I aspire to become. Vanessa's kindness and wisdom have left a profound mark on both my work and my personal growth, and I feel truly fortunate to have had her guidance throughout this journey.

I am also sincerely thankful to my co-supervisor, Professor Keith Hipel. His extensive knowledge and experience in decision-making have taught me invaluable lessons and broadened my perspective in ways I will carry forward in my career.

I would like to express my appreciation to my defense committee members: Professor Evan Davies from the University of Alberta, Professor Juan Moreno-Cruz, Professor Eric Croiset, and Professor Rodrigo Costa from the University of Waterloo. Thank you for your time, feedback, and insightful questions.

Two special thanks go to Professor Neil Craik and Professor Juan Moreno-Cruz. Neil encouraged me to explore the political and regulatory dimensions of my research and sparked my interest in such topics. Juan, with his unique background in economics and engineering, helped me grasp the economic dimensions of my thesis and guided me in building a clear research design, well-defined objectives, and effective use of tools.

While not directly tied to my thesis, Professor Jason Thistlethwaite and Sharmalene Mendis-Millard (Director of Partners for Action) enriched my PhD by connecting me to a broader network of climate change experts through three years of research assistantship, which also provided valuable financial stability. I am grateful to Jason and Sharmalene for their trust in me.

To my friends in Waterloo and London, thank you for your unwavering support, encouragement, and companionship throughout this journey. You not only stood by me but also made the experience joyful and memorable.

Finally, I would like to thank my beloved spouse, Fahimeh. Without her steadfast support, I could not have completed this journey.

Dedication

To my spouse, Fahimeh, whose enduring love, patience, and support carried me through every step of this journey.

To my parents, whose unwavering encouragement and the values they instilled have been the foundation of all I have achieved.

In cherished memory of my grandfather, and with deep gratitude to my grandmother, whose love and guidance remain a lasting source of inspiration.

Table of Contents

Author's Declaration iii

Statement of Contributions iv

Abstract vi

Acknowledgements vii

Dedication viii

List of Figures xiii

List of Tables xv

List of Abbreviations xvi

Chapter 1 Introduction 1

1.1 Background 1

1.2 Problem Statement 3

1.3 Research Outline, Methods and the Structure of the Thesis 4

Chapter 2 Key uncertainties behind global projections of direct air capture deployment 11

2.1 Introduction: The necessity of carbon dioxide removal and roles for direct air capture 12

2.2 Lessons from the AR6 Scenario Database 15

2.3 Key uncertainties affecting projections of direct air capture deployment under different IAM studies 21

2.3.1 Uncertainties regarding socio-economic futures 21

2.3.2 Intergenerational Assumptions: Time Value of Costs and Appetite for Overshoot 26

2.3.3 Maximum Capacity and Growth Rate Limitations 28

2.3.4 Non-Energy Costs of DACCS 29

2.4 Modeling recommendations to explore and better understand the scale and pace of direct air capture deployment 30

2.4.1 Regional Differences and the Need for Context-based Regional Scenarios 30

2.4.2 Modeling both high-temperature (HT) and low-temperature (LT) DAC 31
2.4.3 The necessity of considering both carbon utilization and storage pathways 32
2.4.4 Differences between models, underlying assumptions, and the need for model intercomparison projects 33
2.5 Discussion and Conclusion 35
2.6 References 39
Chapter 3 Applying equity principles leads to higher carbon removal obligations in Canada 48
3.1 Introduction 49
3.2 Results 51
3.2.1 Emission pathways and the role of carbon dioxide removal methods 51
3.2.2 Primary and final energy consumption pathways 54
3.2.3 Potential need for geological storage 57
3.2.4 CDR-related techno-economic uncertainties 57
3.2.5 Future energy pathway and DAC variants availability 62
3.2.6 Growth rates of CDR vs. historical technology adoption in Canada: uncertainties and challenges 64
3.3 Discussion 68
3.4 Methods 70
3.4.1 Equity-based national remaining carbon budget (NRCB) 70
3.4.2 GCAM and CDR representation 72
3.4.3 Scenarios and their socio-technical assumptions 73
3.5 References 78
Chapter 4 The Future of Direct Air Capture in Canada: A Systematic Scenario-Based Exploration of Barriers and Possibilities 83
4.1 Introduction 84

4.2 Methods 87
4.2.1 Scenarios, system descriptors and their variants 87
4.2.2 Workshop 1: Understanding the Interdependencies of the DAC System 90
4.2.3 Cross-Impact Balance (CIB) Analysis for Consistent Scenario Development 91
4.2.4 Workshop 2: Presenting Results and Gathering Feedback 92
4.2.5 Addressing Uncertainties in Expert Judgments and Expanding Scenario Portfolios 93
4.3 Results 94
4.3.1 Perfectly consistent scenarios 94
4.3.2 Marginally inconsistent scenarios 102
4.3.3 Exploring Mental Model Diversity via Ensemble Scenario Analysis 103
4.4 Discussion and Conclusion 106
4.5 References 110
Chapter 5 Adaptation Pathways for Direct Air Capture in Canada: A Proposed Framework for Coordinating Multi-Sectoral Responses to Deep Techno-Economic and Socio-Political Uncertainty 117
5.1 Introduction 118
5.2 Methodology 120
5.2.1 Deep uncertainty 120
5.2.2 Adaptation pathways (AP) 121
5.2.3 The role of systematic scenario development and energy-economy modeling 123
5.3 Results 125
5.3.1 How qualitative scenarios inform quantitative modeling and adaptation pathways 125
5.3.2 Quantitative scenarios informed by CIB 128
5.3.3 Integrating qualitative scenarios, quantitative analysis, and policy reviews into adaptation pathways 133

5.3.4 Describe the current and future situations and objectives (AP Step 1) and problem analysis (AP Step 2) 134
5.3.5 Determine policy options (AP Step 3) 135
5.3.6 Analyze ensembles of scenarios (AP Step 4) 144
5.3.7 Determine the sell-by-date of policy options or packages (AP Step 5) 144
5.3.8 Evaluate policy options and develop pathways (AP Step 6) 147
5.4 Conclusion and next steps 153
5.5 References 156
Chapter 6 Conclusions, Limitations and Future Work 163
6.1 Methodological Insights 165
6.1.1 Integrated Assessment Models: Limitations and Best Practices 165
6.1.2 Cross-Impact Balances for Qualitative Scenario Development: Strengths and Applications 167
6.1.3 Adaptation Pathways as a Tool for Decision-Making Under Deep Uncertainty 168
6.2 DAC-Specific Insights by Chapter 170
6.3 Limitations and Future Work 174
References 177
Appendix A Supplementary Information of Chapter 2 210
Appendix B Supplementary Information of Chapter 3 222
Appendix C Supplementary Information of Chapter 4 241

List of Figures

Figure 1-1. Workflow of the chapters, research objectives, and applied methods 5
Figure 2-1. Distribution of GDP|PPP and population among AR6 deep mitigation scenarios 16
Figure 2-2. A comparison of 1.5 °C scenarios (C1 and C2) with high (above 600 $GtCO_2$) and low (lower than 279 $GtCO_2$) CDR deployment in the second half of the century 19
Figure 2-3. AR and BECCS deployment in 1.5 °C scenarios (C1 and C2 categories) of the AR6 database compared to the sustainable potentials suggested by Fuss et al. (2018) 20
Figure 2-4. Variations in the regional deployment of DACCS among scenarios 31
Figure 3-1. Emissions and removals by sector in Canada. 53
Figure 3-2. Primary energy production in Canada 55
Figure 3-3. Final energy consumption by modes in Canada 56
Figure 3-4. Required carbon storage in net-zero and equity-based scenarios in Canada 59
Figure 3-5. CO_2 Emissions and removals under different techno-economic uncertainties in Canada. 61
Figure 3-6. Future energy characteristics under alternative socio-technological pathways in Canada 63
Figure 3-7. CO_2 Emissions and removals under alternative socio-technological pathways in Canada 64
Figure 3-8. Comparative analysis of growth rates for carbon dioxide removal technologies and historically adopted technologies in Canada. 67
Figure 3-9. Remaining carbon budgets for Canada under different equity principles. 72
Figure 4-1. Distribution of descriptor variants across different levels of DAC competitiveness.. 105
Figure 4-2. Active–passive diagram across scenario ensembles 106
Figure 5-1. Steps involved in building the adaptation pathways map (a), and a schematic illustration of an adaptation pathways map (b), adapted from Haasnoot et al. (2013). 123
Figure 5-2. Emissions and removal by sector for different DAC demand scenarios: a) Very Low DAC Demand, b) Low DAC Demand, c) Moderate DAC Demand, d) High DAC Demand 132
Figure 5-3. DAC demand and final energy requirements across scenarios: a) DAC deployment levels, b) Electricity demand for DAC, c) Natural gas consumption by DAC 133
Figure 5-4. An adaptation pathways prototype for the economic aspects of direct air capture deployment in Canada 149

Figure 5-5. An adaptation pathway prototype for the electricity supply aspects of direct air capture deployment in Canada 152
Figure 5-6. An adaptation pathway prototype for the CO_2 storage 152

List of Tables

Table 2-1. Characteristics of two main variants of DAC technology 13
Table 2-2. Categories of deep mitigation scenarios from the AR6 database 15
Table 2-3. Reviewed integrated assessment modeling studies 22
Table 2-4. Scenarios including DACCS selected from peer-reviewed studies for further analysis and their DACCS-related characteristics 23
Table 2-5. Factors affecting DACCS deployment in different IAM studies. 25
Table 3-1. Defining scenarios, their underlying logic and techno-economic assumptions 75
Table 4-1. CIB descriptors and their variants for the direct air capture system 89
Table 4-2. Numerical and qualitative judgements in CIB 90
Table 4-3 . Scenario tableau of the perfectly consistent scenarios for Canadian DAC system 98
Table 4-4. Summary impact table of scenario 6 100
Table 4-5. Summary impact table of scenario 13 101
Table 5-1. Complementary methods for understanding climate and socio-technological systems: CIB and GCAM 125
Table 5-2. Internally consistent scenarios of Canadian DAC landscape (Source: Chapter 4) 127
Table 5-3. Economic and Electricity Supply Measures and Frameworks for Direct Air Capture Deployment 138
Table 5-4. Policy packages for the economic dimension and the rationale behind their effectiveness and sell-by-dates 145

List of Abbreviations

Term	Acronym
Adaptation Pathways	AP
Advanced Market Commitment	AMC
Afforestation/Reforestation	AR
Bioenergy with Carbon Capture and Storage	BECCS
Carbon Capture and Storage	CCS
Carbon Capture, Utilization and Storage	CCUS
Carbon Dioxide	CO_2
Carbon Dioxide Removal	CDR
Carbon Removal Obligation	CRO
Carbon Take-Back Obligation	CTBO
Contracts for Difference	CfD
Cross-Impact Balances	CIB
Decision-Making Under Deep Uncertainty	DMDU
Degree Celsius	ºC
Direct Air Carbon Capture and Storage	DACCS
Direct Air Carbon Capture and Utilization	DACCU
Direct Air Capture	DAC
Direct Ocean Carbon Capture and Storage	DOCCS
Enhanced Weathering	EW
Equal Per-Capita (Qualified)	EPC-Q
Exploration, Regulation, Expansion, and Utilization	EREU
Global Change Assessment Model	GCAM
Greenhouse Gas Emissions	GHG
Gross Domestic Product	GDP
Gross Domestic Product based on purchasing power parity	GDP|PPP
High-Temperature	HT
High-Temperature DAC Supplied by Electricity	HT-DAC-Elec

Term	Acronym
High-Temperature DAC Supplied by Natural Gas	HT-DAC-NG
Hydrogen	H_2
Integrated Assessment Model	IAM
Intergovernmental Panel on Climate Change	IPCC
Investment Tax Credit	ITC
Low-Temperature	LT
Low-Temperature DAC Supplied by Electricity	LT-DAC-Elec
Monitoring, Reporting, and Verification	MRV
National Remaining Carbon Budgets	NRCB
Negative Emissions Technology	NET
Output-Based Pricing System	OBPS
Per Capita Convergence (Qualified)	PCC-Q
Photovoltaic	PV
Power Purchase Agreement	PPA
Production Tax Credit	PTC
Remaining Carbon Budget	RCB
Sixth Assessment Report	AR6
Social Discount Rate	SDR
Shared Socio-Economic Pathways	SSP
Socio-Technological Change	STC
Sustainable Development Goals	SDG

Chapter 1
Introduction

1.1 Background

To meet the goals of the Paris Agreement, limiting global warming to well below 2°C and ideally to 1.5°C above pre-industrial levels, the world must adhere to a finite carbon budget (Rogelj et al., 2019). This budget sets a cap on the amount of carbon dioxide (CO_2) that can be emitted without triggering dangerous levels of climate change. As this budget is rapidly being depleted, nations are increasingly adopting net-zero targets, aiming to balance residual emissions with an equivalent amount of carbon dioxide removal (CDR)—a suite of methods that extract CO_2 directly from the atmosphere and store it in land, ocean, or geological reservoirs (IPCC, 2022; Lamboll et al., 2023; Matthews et al., 2020). Moreover, given the current trajectory of global emissions, it is likely that the 1.5°C target will be exceeded, a phenomenon referred to as temperature overshoot (Reisinger & Geden, 2023). To reverse this overshoot and bring atmospheric CO_2 concentrations back within safe limits, substantial negative emissions will be required in the second half of the century (Pelz et al., 2024). CDR is increasingly seen as essential not only for compensating residual emissions from hard-to-abate sectors but also for delivering net-negative emissions post-net-zero to reverse temperature overshoots (Ganti et al., 2024).

CDR methods vary widely in terms of technological maturity, scalability, environmental footprints, and social acceptance. They can be broadly categorized into conventional land-based methods, such as afforestation and reforestation and novel approaches that mostly use chemical methods to capture CO_2 such as bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), and ocean-based methods like alkalinity enhancement (S. M. Smith et al., 2023). In the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), scenarios that meet Paris-aligned targets project conventional CDR deployment in 2100 to range from approximately 2 to 4.5 $GtCO_2$/year, and novel CDR methods to range from 3.3 to 16.2 $GtCO_2$/year. While conventional CDR currently removes around 2 $GtCO_2$/year, novel CDR methods remain at less than 1 $MtCO_2$/year—far below the levels envisioned in the IPCC AR6 scenarios (Byers et al., 2022; Gidden et al., 2023).

Among different CDR methods, DAC has garnered considerable attention from governments (Low et al., 2024) and the private sector (Wang et al., 2024). DAC systems chemically bind CO_2 from ambient air, which is then either stored underground (DACCS) or utilized in commercial applications (DACCU). Despite its current high costs and energy requirements, DAC offers compelling advantages: siting flexibility, a relatively low land and water footprint, high measurement certainty, and the potential

for permanent storage (Fuss et al., 2018; Motlaghzadeh et al., 2023). These features have attracted growing interest from policymakers, industry, and researchers (Bouaboula et al., 2024). While DAC is gaining traction as a critical component of future mitigation strategies, the scale and timing of its deployment remain deeply uncertain. Pathways assessed in the IPCC AR6 and in individual Integrated Assessment Model (IAM) studies project DAC deployment ranging from negligible levels to nearly 40 $GtCO_2$/year by 2100. This enormous range reflects divergent assumptions about socio-economic development, mitigation ambition, technology learning rates, and the role of other CDR methods (Motlaghzadeh et al., 2023).

Together, these uncertainties interact with each other and form a case of "deep uncertainty," where stakeholders cannot agree on a single set of assumptions or even the probability distributions of possible futures. This challenges traditional policy approaches that rely on a small number of plausible deterministic projections and emphasizes the need for tools that can accommodate a broad range of plausible futures (Maier et al., 2016). Beyond modeling uncertainties, DAC faces numerous real-world barriers that could constrain its deployment. Key challenges identified in the literature include high capital and operational costs (Lackner & Azarabadi, 2021; McQueen et al., 2020; Sievert et al., 2024; Young et al., 2023), significant energy requirements (Chatterjee & Huang, 2020), public skepticism (Keeley et al., 2025; Satterfield et al., 2023), inadequate policy and regulatory frameworks (Sovacool et al., 2022), and limited CO_2 transportation and storage capacity (Craik et al., 2021). These barriers are deeply interconnected, forming complex relationships that further obscure the path forward for DAC deployment. For instance, public acceptance of DAC might be influenced by its currently high costs—ranging from $400 to $3,000 per ton of net CO_2 captured (Young et al., 2023). In a survey conducted by Sovacool et al. (2022), some experts expressed concern about the technology's heavy reliance on public funding and the risk that costs may not decrease over time, potentially straining public finances and undermining social acceptability.

Despite these uncertainties and barriers, the need to act remains urgent. If DAC is to play a role in helping countries meet their net-zero and post-net-zero commitments, strategic decisions must be made today to guide investments, develop enabling infrastructure (e.g., CO_2 transportation and sequestration), and craft coherent policies. These decisions must be robust to future uncertainties and flexible enough to adapt to new developments. Decision-makers therefore need frameworks that can integrate knowledge from multiple domains, understand the uncertainties and their interactions and help evaluate the robustness of policy choices under "deep uncertainty" which often applies to emerging technologies (Kapoor & Klueter, 2021) like DAC, where cost reductions, social acceptance, and global deployment levels are not easily predictable.

1.2 Problem Statement

This study focuses on Canada, recognized as one of the top ten countries worldwide in terms of per-capita emissions (Friedlingstein et al., 2023; Our World in Data, 2023). In 2022, Canada announced its Emissions Reduction Plan, outlining a framework of federal policies to reduce emissions to 40%-45% below 2005 levels by 2030 and set a long-term target of reaching net-zero greenhouse gas emissions by 2050. Given its historical emissions and relatively high responsibility for climate change, Canada may require significant amounts of CDR post-2050 to address its carbon debt and contribute to reversing global temperature overshoots (Motlaghzadeh et al., 2025). A portfolio of CDR methods, potentially including DAC, will be essential for achieving net-zero emissions and addressing temperature overshoots through negative emissions beyond net zero.

Overall, there are two key areas Canada must address to effectively integrate CDR and DAC into its climate strategy. First is the need to understand the future demand for DAC and CDR more broadly, as well as the deep uncertainties specific to the Canadian context that shape these potential futures. This involves identifying the key drivers that define the future landscape of DAC, how they interact, and what internally consistent narratives could emerge for DAC deployment in Canada. Such analysis not only informs the potential scale of DAC deployment but also enhances the credibility and relevance of scenarios by clarifying *why* certain futures are plausible. Once potential DAC demand trajectories and their narratives are understood, the second focus area is to assess current and proposed policies in light of these scenarios. The goal is to identify and prioritize policy options or pathways (i.e., a sequence of policies) that remain effective across a wide range of futures, recognizing that no single scenario can be assigned a definitive probability. This approach ensures decisions are robust under uncertainty and adaptable to emerging developments.

For the first area, understanding potential futures for DAC technology and framing associated uncertainties, previous modeling studies have examined plausible DAC deployment pathways in Canada, focusing primarily on quantifiable factors. The Canada Energy Regulator (2023) projected a DAC contribution of 44–55 $MtCO_2$ by 2050. Navius Research (2021) found that in all scenarios where DAC is assumed to be available, it plays a significant role in achieving net-zero emissions, with removal ranging from 307 to 426 $MtCO_2$ in 2050. Bailie et al. (2023) projected a more modest DAC deployment of 5.4–9.8 $MtCO_2$ by 2050. All of these studies have primarily focused on the role of DAC in achieving net-zero targets, where it is used solely to offset residual emissions. However, no study has explored the potential role of CDR and DAC in the post-net-zero period for reversing temperature overshoot, a challenge that is becoming increasingly urgent as the world nears the 1.5°C threshold (Pelz et al., 2024; Prütz et al., 2023), particularly through the lens of burden-sharing principles. This remains a key source

of uncertainty that has been largely underexplored. Moreover, existing studies have not examined the broader narratives of possible futures that incorporate qualitative system elements (e.g., public acceptability of DAC) or how various sources of uncertainty may interact to shape DAC deployment pathways.

Turning to the second area, assessing current and proposed policies across alternative future scenarios, Canada has begun to take initial steps toward supporting the development of a carbon removal industry. The federal industrial carbon price is scheduled to reach C$95 per tonne in 2025 and increase to C$170 by 2030. Large industrial emitters operate under an Output-Based Pricing System (OBPS), which allows them to either pay the carbon price or use eligible compliance credits (Government of Canada, 2025). To complement this, the federal government is developing a greenhouse gas offset system, including a draft protocol for DAC with geological storage. Once finalized, this protocol would enable DAC projects to generate compliance credits under the OBPS. In Budget 2022, the government introduced a refundable CCUS Investment Tax Credit, offering up to a 60% credit for DAC equipment, 50% for other capture technologies, and 37.5% for transport and storage infrastructure (Canada Revenue Agency, 2024). Additionally, in 2025, the federal government committed $10 million through 2030 for the purchase of carbon removal credits from industry, signaling early steps toward public procurement of CDR (Treasury Board of Canada Secretariat, 2024).

While these measures reflect growing policy interest, no study has yet evaluated the effectiveness of Canada's existing and proposed instruments across a wide range of possible DAC futures. Existing studies fall short in capturing how future uncertainties interact within complex systems to shape DAC deployment, and they often lack qualitative narratives that explain why such outcomes may arise. Moreover, there is little guidance on how to make policy decisions that remain robust under conditions of deep uncertainty, where future DAC demand could vary significantly. Key questions remain unanswered, for example: Are current carbon prices and their projected increases sufficient to incentivize large-scale DAC deployment? How far can investment tax credits support deployment before needing to be scaled back or replaced? What is the potential scale of public procurement, and when should Canada consider transitioning to new or additional policy instruments? In a post-net-zero world, where CDR demand may exceed residual emissions, what economic policies will be required to support ongoing removals?

1.3 Research Outline, Methods and the Structure of the Thesis

As shown in Figure 1-1, this thesis aims to systematically investigate the uncertainties shaping the future of DAC in Canada (Chapter 2 and Chapter 3), explore how these uncertainties

interact (Chapter 4), and identify appropriate policy actions under alternative plausible demand trajectories (Chapter 5). Ultimately, the goal is to develop a prototype of a decision-support framework that connects these uncertainties with near-term actions and long-term policy strategies, enabling Canada to make adaptive, robust, and forward-looking decisions under deep uncertainty (Chapter 5). To achieve this goal, the thesis integrates three complementary systems-based methodologies outlined below. Further details on each of these methodologies are provided in the chapters where they are applied.

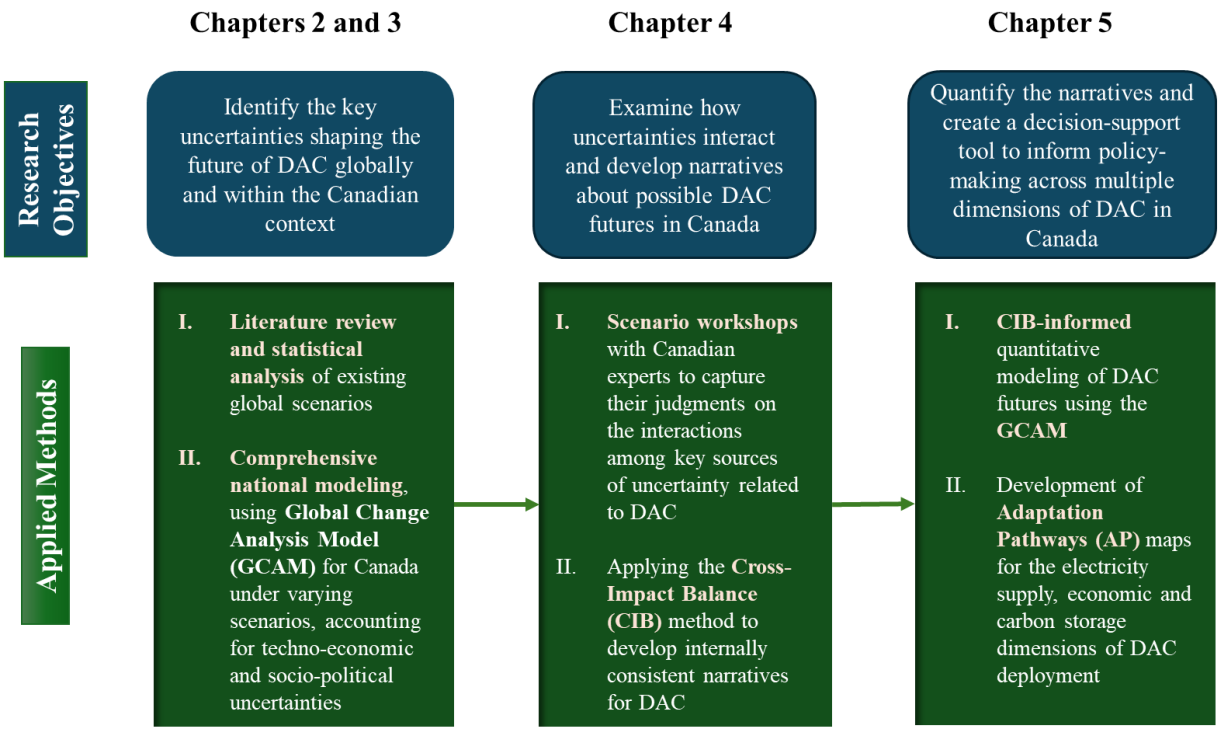

Figure 1-1. Workflow of the chapters, research objectives, and applied methods

Global Change Analysis Model (GCAM; Chapter 3 and Chapter 5): To quantify Canada's potential DAC demand under varying global and national assumptions, analyses were performed with GCAM (Joint Global Change Research Institute, 2023). GCAM is a widely used integrated assessment model (IAM) that links economic, energy, land-use, water, and climate systems. GCAM is a comprehensive integrated assessment tool that simulates interactions between energy, water, land, economy, and climate systems across 32 global regions. It finds the market equilibriums from 1990 to 2100 with updates every five years. By integrating these systems within its core rather than treating them as separate modules, GCAM provides insights into macroeconomic trends, energy supply and

demand, agriculture and land use changes, and water usage, underpinned by population and productivity projections. Since the primary goal of this study is to understand the role of CDR, and DAC in particular, we used a modified version of the GCAM V5.4 (in Chapters 3 and 5) that includes a diverse portfolio of CDR technologies (Fuhrman et al., 2023). This version of GCAM treats Canada as a separate region, enabling the implementation of Canada-specific climate policies and CDR pathways. The model also includes three DAC variants: high-temperature solvent-based processes (HT-DAC) powered by either electricity or natural gas, and low-temperature (LT-DAC) systems powered exclusively by electricity. It also includes other CDR methods such as BECCS, enhanced rock weathering, biochar, and direct ocean carbon capture and storage. Previous studies have shown that incorporating a wider range of CDR technologies improves the sustainability of modeling outcomes by distributing CDR demand more evenly across methods, thereby reducing the risk of overreliance on any single technology—especially those with potentially negative environmental impacts (Fuhrman et al., 2023). In Chapter 3, GCAM is used to develop multiple Canadian net-zero and post-net-zero scenarios that incorporate equity principles, addressing the previously identified research gap and providing a clearer understanding of the potential range of CDR and DAC deployment in the Canadian context. In Chapter 5, GCAM was used to quantify the selected internally consistent scenario narratives identified through the CIB analysis in Chapter 4.

While there are also several other IAMs, this study specifically employs the modified version of GCAM V5.4 developed by Fuhrman et al. (2023) for several reasons. First, it offers a diverse and detailed representation of CDR technologies, including multiple DAC variants, which is essential for the focus of this research. Second, Canada is modeled as an independent region, allowing the implementation of Canada-specific climate policies and CDR pathways. Third, GCAM is a technology-rich, multisectoral model that captures interactions across energy, land, water, industry, and the broader economy—an important feature for studying the sustainability and energy implications of removal strategies. Fourth, GCAM has a well-established history in modeling CDR technologies. Finally, GCAM is fully open-access, including its underlying code and solution algorithms, unlike many other IAMs (e.g., TIMES, IMAGE, WITCH), which require licenses or restrict access to key components.

Cross-Impact Balances (CIB; Chapter 4): The CIB method is a semi-quantitative scenario-building approach that identifies internally consistent future pathways by analyzing the interdependencies among key system drivers, known as scenario descriptors. These descriptors represent crucial socio-political, technological, and economic elements that shape system evolution. They are typically selected through structured literature reviews, expert engagement, or research team elicitation, with an emphasis on elements that strongly influence system behavior and clarify core

cause-effect relationships. Each descriptor is assigned a set of variants, which are plausible, alternative future states, that must be both comprehensive and mutually exclusive to ensure analytical clarity (Weimer-Jehle, 2006, 2023). For example, a descriptor like DAC cost might include "low," "moderate," and "high" cost variants, each clearly defined. Scenarios are constructed by combining one variant from each descriptor, resulting in a set of possible future outcomes and commensurate system influences. The CIB method then assesses the logical consistency of these scenarios based on how descriptor variants support or contradict each other through their commensurate influences, helping to distinguish stable, internally consistent scenarios from inconsistent ones. This structured approach enables a systematic exploration of plausible futures and the dynamics that shape them (Weimer-Jehle, 2006, 2023). Scholars have used CIB to bridge the knowledge originated from multiple disciplines and apply it to different domains, such as the global socio-technical scenarios for climate change research (Schweizer, 2020; Schweizer & Kriegler, 2012; Schweizer & O'Neill, 2014), socio-technical energy and decarbonization scenarios (Kurniawan et al., 2022; Pregger et al., 2020; Prehofer et al., 2021; Schuch et al., 2024; Vögele et al., 2017; Weimer-Jehle et al., 2016, 2020) and climate change adaptation (Lazurko et al., 2022; Wachsmuth, 2015). This method was used in this study (Chapter 4) to identify and map interactions among ten key descriptors of DAC feasibility in Canada, including clean electricity availability, CO_2 storage potential, cost trajectories, policy coherence, and social perception of the technology. Using input from DAC experts during a structured workshop process, the CIB analysis produced a set of internally consistent and plausible scenarios that reflect the range of uncertainty in DAC's socio-technical context. These scenarios served both as a diagnostic tool to reveal hard constraints and enablers, and as a foundation for quantification and DAC deployment pathways analysis in subsequent steps.

CIB was selected over other scenario discovery methods because it uniquely captures the complex, cross-sectoral interdependencies that shape DAC deployment in Canada—many of which, such as policy coherence or public acceptance DAC, cannot be robustly quantified yet significantly influence system behavior. In contrast, statistical scenario discovery tools like PRIM or CART require large numerical datasets to function effectively (Lempert et al., 2008), while narrative approaches such as intuitive logics (Wright et al., 2013) or story and simulation do not formally test internal consistency and may risk producing overly optimistic or biased scenarios (Schweizer, 2020). CIB provides a transparent, semi-quantitative structure that can explicitly represent how socio-political, techno-economic, and environmental drivers influence one another within a complex system. Its focus on identifying internally consistent combinations of descriptor variants also offers a strong advantage for integration with quantitative modeling. In this study, CIB scenarios are systematically translated into

GCAM inputs in a way that purely verbal analysis cannot support as rigorously (Schweizer, 2020). For these reasons, CIB offered the most appropriate and defensible methodology for this research.

Adaptation Pathways (AP; Chapter 5):

The future of CDR and DAC deployment in Canada is characterized by deep uncertainty, meaning that decision-makers lack reliable knowledge of—or cannot agree on—the correct system model, the key outcomes and their relative importance, or the probabilities of different inputs and events (Lempert, 2003; Walker et al., 2013). Such conditions produce a wide range of plausible models, conflicting stakeholder preferences, uncertain parameters, and multiple potential decision pathways (Kwakkel et al., 2016; Kwakkel et al., 2010). Conventional approaches—such as optimizing a single predicted future or maximizing expected utility—struggle under these circumstances because future impacts cannot be reliably forecasted and stakeholders do not share a common basis for evaluating outcomes (Lempert, 2003; Stanton & Roelich, 2021). Decision-making under deep uncertainty (DMDU) techniques were developed to address these challenges, but they vary in how they support decisions. Methods like Robust Decision Making (RDM) stress-test strategies across many futures but focus on static plans. In contrast, the Adaptation Pathways (AP) method is specifically designed for long-term, dynamic decision contexts like DAC: it sequences decisions over time, identifies when strategies will fall short, and maps flexible pathways that accommodate evolving knowledge and conditions. This framework provides a structured and adaptive approach to decision-making in contexts where both probabilities and the range of potential outcomes are unknown (Haasnoot, 2013). By mapping multiple pathways and identifying critical decision points, moments when policies and actions fail to achieve their objectives are found (Marchau et al., 2019). AP facilitates the development of flexible and adaptive strategies. These strategies can adjust to evolving conditions, stakeholder priorities, and shifting policy landscapes. AP, along with its sister method, Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013), has been widely applied to problems involving deep uncertainty, such as water resource management and planning (e.g., flood management) (Carstens et al., 2019; Haasnoot, 2013; Muccione et al., 2024), transportation, sustainability (Butler et al., 2016) and agriculture and forestry (Cradock-Henry et al., 2020; Vizinho et al., 2021). A recent review of these applications (Haasnoot et al., 2024) found that the deployment of adaptation pathways has resulted in greater confidence among decision makers by identifying robust policy choices that remain viable under future uncertainty. Additionally, when combined with participatory processes that incorporate community values, adaptation pathways have contributed to building trust in decision-making, particularly in contexts where conflicting interests and power asymmetries exist among public and private decision agents (Haasnoot et al., 2024). In this study, the AP framework is used to integrate insights from qualitative CIB-based scenarios and

quantitative GCAM modeling, creating a unified decision-support tool for Canadian DAC policymakers. This combined approach is novel in three ways: it links socio-political drivers with techno-economic modeling, it translates uncertain DAC futures into time-sequenced policy choices, and it identifies demand-based tipping points where current policies may no longer be effective. Prototype AP maps were developed for three key domains—electricity infrastructure, economic instruments, and CO_2 storage—and these maps show how different levels of DAC deployment may require distinct policy actions and when shifts to new policies become necessary as critical thresholds are reached.

This thesis proceeds through four main chapters:

Chapter 2: "Key uncertainties behind global projections of direct air capture deployment"
Published in Applied Energy, *October 2023*.
This chapter provides a review of DAC scenarios featured in the IPCC AR6 database and individual IAM studies. It identifies the key assumptions driving the wide variability in global DAC projections, including the persistence of fossil fuel use, the range of CDR methods considered, socio-economic development pathways, ethical and equity considerations, cost trajectories, and deployment constraints. Furthermore, this chapter establishes the global uncertainty landscape and motivates the need for multi-method, context-specific assessments.

Chapter 3: "Applying equity principles leads to higher carbon removal obligations in Canada"
Published in Communications Earth & Environment, *February 2025*.
This chapter applies burden-sharing principles within a modified version of the GCAM model to quantify Canada's post-2050 carbon removal obligations. It explores how adopting equity-based national remaining carbon budgets (NRCBs) influences the scale and timing of CDR deployment. Results suggest that Canada may need to remove up to 20.3 $GtCO_2$ between 2050 and 2100 under certain equity principles, with DAC playing a central role. The chapter also compares projected CDR growth rates to historical trends in Canadian technology adoption to assess feasibility.

Chapter 4: "The Future of Direct Air Capture in Canada: A scenario-based exploration of barriers and possibilities"
The contents of this chapter have been incorporated into a manuscript that is under review at Energy Research & Social Science.
Using CIB analysis informed by expert input, this chapter develops internally consistent qualitative scenarios that capture the key socio-political and techno-economic conditions shaping DAC deployment in Canada. It identifies critical barriers, including high costs, fragmented regulation, and

limited public acceptance, and examines how different configurations of these factors lead to plausible pathways of DAC success or failure.

Chapter 5: "Adaptation Pathways for Direct Air Capture in Canada: A Proposed Framework for Multi-Sectoral Responses to Deep Techno-Economic and Socio-Political Uncertainty"

Contents from this chapter will be incorporated into a manuscript being prepared for submission to the call for papers entitled "Adaptation Pathways and Scenarios for Climate Change Research" with npj Climate Action.

Building on the scenarios developed in Chapter 3 and Chapter 4, this chapter applies the AP framework to map near-term policy actions and long-term strategies. It focuses on three key decision domains: (1) economic instruments (e.g., carbon pricing, mandates), (2) electricity supply and infrastructure (e.g., siting, grid integration) and (3) CO_2 storage. Prototype AP maps are presented to illustrate how decisions can be sequenced and adjusted over time in response to evolving DAC demand. This chapter highlights the value of integrating multiple modelling methods to address uncertainty in a structured and policy-relevant way.

Chapter 6: Conclusions, Limitations, and Future Work

This chapter reviews the strengths and limitations of the methodologies employed and highlights the insights gained from linking them together. It emphasizes that such integration is particularly valuable in contexts of deep uncertainty associated with novel technological change. The chapter also synthesizes DAC-specific insights from each preceding chapter and concludes with a discussion of study limitations and recommendations for future research.

Chapter 2

Key uncertainties behind global projections of direct air capture deployment[1]

Abstract

To limit global warming to levels set in the Paris Agreement, integrated assessment modeling highlights the necessity of removing gigatons of carbon dioxide. Direct air capture is one of the potential methods for carbon dioxide removal and has gained significant attention despite being a relatively new technology. While some scenarios can meet Paris targets without relying on direct air capture, other models show the need for up to 38 gigatons/yr of removal by this technology. Such wide variation in projections reflects uncertainty over the feasibility of deploying direct air capture at scale and points the need for greater attention to the model assumptions driving this variation. This study provides a comprehensive review of scenarios from the Intergovernmental Panel on Climate Change Sixth Assessment Report and peer-reviewed studies focusing on direct air capture as a mitigation strategy. The review identifies several key factors contributing to uncertainty in direct air capture projections, including prolonged fossil fuel use, diversity of carbon removal methods, future socio-economic conditions, intergenerational assumptions, deployment limitations, and technology costs. The study recommends conducting multi-model assessments of direct air capture scenarios due to the influence of various assumptions and model structures on projections. The authors also suggest including different variants of direct air capture technology and both carbon utilization and storage pathways in future models, as these factors can impact system demands, economic efficiency, and public acceptability.

Keywords: Climate Change Mitigation; Carbon Dioxide Removal, Direct Air Capture, Negative Emissions, Integrated Assessment Model

[1] This is an Accepted Manuscript of an article published by Elsevier in *Applied Energy* on 15 October 2023, available online: https://doi.org/10.1016/j.apenergy.2023.121485. K. Motlaghzadeh, V. Schweizer, N. Craik and J. Moreno-Cruz, "Key uncertainties behind global projections of direct air capture deployment"

2.1 Introduction: The necessity of carbon dioxide removal and roles for direct air capture

The Paris Agreement identified the objective of limiting global warming to well below 2 °C (end-of-century temperature compared to the pre-industrial level) and pursuing limits to 1.5 °C to prevent the dangerous impacts of climate change[1]. To find the pathways compatible with these targets, energy-economy modelers take advantage of integrated assessment models (IAMs), which are designed to capture the interdependencies, system linkages and feedback between biophysical systems and socio-economic characteristics of possible futures to identify trajectories of greenhouse gas emissions (GHG)[2]. Different IAMs have investigated pathways that may plausibly limit increases in global warming to levels of less than 2 or 1.5 °C at the end of the century[3,4]. Within these pathways, carbon dioxide removal (CDR) plays an increasingly important role.

CDR refers to processes (practices or technologies) that reduce the concentration of CO_2 in the atmosphere[6–8]. The effect of CDR on atmospheric levels of CO_2 is similar to emission reductions and may be preferred where removals of CO_2 can be achieved at a lower cost than emission reductions. CDR may be beneficial for offsetting residual emissions in hard-to-abate sectors or non-CO_2 emissions[3]. In addition, many pathways consistent with the Paris Agreement targets project that global emissions should be balanced between emissions and removals of greenhouse gases between 2050 and 2070[9,10]. However, these pathways may have a period where the Paris Agreement temperature targets are exceeded, a condition referred to as temperature overshoot. Atmospheric CO_2 concentrations are then drawn down through subsequent deployment of CDR at net-negative levels (net removals exceed net emissions).

CDR takes a wide variety of forms, and while there are different CDR categorization schemes[11], one approach clusters different methods into nature and technology-based ones. The former consists of practices that try to enhance the natural processes that uptake CO_2 (e.g., soil carbon management and enhanced weathering) and methods such as afforestation/reforestation (AR) that remove CO_2 by changing land use[12]. Two well-established technology-based methods are bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC). CDR methods differ in their environmental footprints and sustainability implications, technological readiness, the feasibility of deployment, potential, storage permanency, costs and public acceptability[13,14]. Despite the significant reliance on CDR in pathways meeting the Paris Agreement targets, the current deployment scales for most novel methods (e.g., DAC and BECCS) are negligible[15].

This study focuses on DAC as a relatively new technology with uncertain high costs and energy requirements. DAC captures CO_2 by binding it to sequestration materials, followed by a regeneration

step, where the captured carbon is released, and the sequestration materials are prepared for reuse. Capturing materials can be in liquid (solvent) or solid (sorbent) form. DAC systems based on solvents typically require a higher temperature heat energy than solid sorbents[16]. Table 2-1 shows that these two DAC variants' system demands, costs, and environmental footprints vary substantially. Further details about the capturing process and system demands of DAC are provided in Section A1 of Appendix-A. Even with the current high costs and energy requirements, DAC appears to have some characteristics, such as large-scale CO_2 removal potential, siting flexibility (although limited by geological storage and availability of low-carbon energy sources), low direct land and water footprint (compared to BECCS and AR), carbon storage permanency and high measurement certainty, that has attracted the attention of policy-makers, industries and academics[17–19].

Table 2-1. Characteristics of two main variants of DAC technology

System Demands of Direct Air Capture	**Direct Air Capture Technology Variants**	
	HT-DAC	**LT-DAC***
Required Temperature for Thermal Energy (°C)	800-900[16]	80-120[16]
Thermal Energy Requirements (GJ/tCO_2)	7.7-10.7[16]	3.4-4.8[16]
Required Electricity (GJ/tCO_2)	0.74-1.7[16]	0.55-1.1[16]
Water Demand (tH_2O/tCO_2)[a]	5[20]	3[20]
Land for 1$GtCO_2$ removal (10^3 Km^2/year)[b]	20[20]	11.5[20]
Required Sorbent/Solvent (Mt) for 1 $GtCO_2$ removal	6[20]	3[20]
Material Use (Mt) for 1 Gt CO_2 removal	17[20]	36[20]
Capture Costs ($/$tCO_2$)[c]	147-279[16]	88-228[16]

a. Water demand for BECCS is 300 to 750 (tH_2O/tCO_2)[21]

b. The land requirement for 1 Gt CO_2 removal by BECCS is around 300-1100 (10^3 Km^2/ year)[21]

c. These capture costs do not consider the CO_2 emitted for supplying the energy requirements. Detailed cost analysis is available at Fasihi et al.[79] and the National Academies of Sciences, Engineering, and Medicine[16].

* LT-DAC has different variants, and the system demands shown in this table are for a system called "Temperature Swing Adsorption or TSA"[22].

The captured carbon from DAC may be utilized for various applications or stored in geological reservoirs. Direct air carbon capture and utilization (DACCU) might have different carbon balance implications and climate change effects from direct air carbon capture and storage (DACCS). DACCS is a "negative emissions" system from a carbon balance standpoint. However, depending on the utilization pathway, DACCU might only be carbon neutral, where, for example, the captured carbon is being used to produce carbon-based fuels[23]. In this paper, our primary focus will be on DACCS, as it has been predominantly examined in modeling studies, with only a few exceptions where DACCU has also been considered[24].

The deployment rate of DACCS in pathways meeting the Paris Agreement temperature targets varies by multiple orders of magnitude among different modeling studies, covering the range of 0 to 18.9 $GtCO_2/year_{2100}$ for such scenarios available in the AR6 database[25]. The top end of these projections rises to around 39 $GtCO_2/year_{2100}$ when looking at scenarios from other peer-reviewed studies that investigate the role of DACCS. The substantial variation in DACCS deployment rates across different modeling studies presents a challenge to the fundamental role of IAMs in informing decision-makers. Despite notable studies on DACCS, the existing literature needs a comprehensive review that consolidates the scattered information from various studies and investigates the plausible reasons behind such variations. This paper addresses this research gap by conducting an in-depth analysis of modeling assumptions and findings. Furthermore, this study proposes best modeling practices for future research by incorporating insights from different studies and disciplines. By focusing our attention on the central drivers influencing DACCS deployment, this paper enables better identification of realistic assumptions and a better understanding of pathways' social, environmental, and technical implications, including DACCS and other CDR methods, which will be essential to generate better models, communicate the embedded uncertainties regarding DACCS deployment and enhance the interpretability of the results by readers and decision-makers[26–28,18,29–33,25].

To draw conclusions about what factors are most influential on DACCS deployment, this article examines two complementary scenario sources: (1) aggregated information from the AR6 database[25] and (2) individual published IAM studies (all but one of them being available in the AR6 database) that include more detailed information on socio-technical and economic modeling assumptions for DACCS than is available in the first set of scenarios[26–28,18,29–33]. The AR6 scenarios database allows for a comparison of a large number (700) of scenarios with different compositions of CDR. The AR6 scenario database only hosts the outputs of scenario studies, and the underlying assumptions (including study design and model structure) of modeling studies matter. We, therefore, consulted peer-reviewed studies of DACCS deployment to capture dimensions that cannot be determined from the AR6 database alone. This set of nine studies is summarized in Table 2-3. Reviewed integrated assessment modeling studiesand provides in aggregate, 54 scenarios that offer greater transparency and detail on key CDR-related assumptions for further review in this article. By comparing the scenarios which differ in critical dimensions, we can make observations concerning the influence of these factors, which provides insight into significant uncertainties.

The paper proceeds as follows. Section 2.2 analyzes the AR6 database regarding total CDR deployment and narrows the focus to DACCS and its interaction with BECCS and AR. Section 2.3 introduces and examines the 54 DACCS scenarios, discussing the key factors that drive significant

variation among model projections. We describe the differences found in the identified studies in four categories: 1) uncertainties regarding socio-economic futures, 2) intergenerational assumptions, 3) maximum capacity and growth rate limitations and 4) costs of DACCS. Drawing on Sections 2.2 and 2.3, Section 2.4 analyses the areas that appear likely to be valuable for further investigation to better model and realize the DACCS system. The conclusion section summarizes the main findings from this study, its limitations and suggests directions for future research.

2.2 Lessons from the AR6 Scenario Database

The AR6 scenarios database categorizes scenarios based on the climate change target they are designed to meet. We review four categories of these pathways: C1, C2, C3 and C4 as shown in Table 2-2. Categories of deep mitigation scenarios from the AR6 database. These deep mitigation scenarios maintain the temperature increase below 1.5 or 2 °C[28,34], with variations in probability and overshoot. On average, these four categories not only use CDR as negative emissions but also, compared to scenarios meeting less stringent mitigation targets than 2°C, include a higher share of low-carbon energy, a higher electricity share in final energy, less CO_2 intensity of primary energy, less energy demand and fewer non-energy GHG emissions[4]. Depending on the temperature goal and probability of overshoot, the timing of net-zero global CO_2 emissions will occur around 2055 to 2085. After reaching net zero, net-negative emissions are between 1 to 10 $GtCO_2$ (the range is subject to temperature goal and overshoot) to compensate for the earlier positive emissions[4].

Table 2-2. Categories of deep mitigation scenarios from the AR6 database

Scenario Category	Number of Simulated Scenarios	Median Cumulative CDR Deployment ($GtCO_2$)	Number of scenarios that include DACCS	Median [min-max] DACCS Deployment ($GtCO_2$/year)		
				2050	2080	2100
C1	97	659	38	0.3 [0-2.2]	0.8 [0.1-8.8]	2.2 [0.1-13.8]
C2	133	687	33	0.2 [0-2.2]	3.8 [0-20.3]	7 [0-18.9]
C3	311	569	125	0.3 [0, 2]	2.9 [0.1-9.8]	3.4 [0.1-11]
C4	159	553	57	0.3 [0-1.6]	3.1 [0-9.7]	2.4 [0-21]

C1: 1.5 °C end-of-century temperature goal (a probability of greater than 0.5) and no or limited overshoot (probability of peak warming greater than 1.5 °C < 0.67)

C2: 1.5 °C end-of-century temperature goal (a probability of greater than 0.5), but allowing for high overshoot (probability of peak warming greater than 1.5 °C ≥ 0.67)

C3: Likely below 2 °C temperature limit for the whole century (a probability of greater than 0.67)

C4: Below 2 °C end-of-century temperature goal (a probability of greater than 0.5)

In addition to the effects of temperature targets on CDR deployment, models use various technical and socio-economic assumptions as inputs or constraints to produce their results as well as socio-economic factors, such as population and gross domestic product (GDP). Figure 2-1 shows a significant variation in GDP based on purchasing power parity (GDP|PPP) and population assumptions among scenarios. These factors strongly influence future global emissions[35], subsequently affecting the scale at which CDR must be deployed. In the new generations of scenarios, scenario producers have introduced the shared socio-economic pathways (SSPs) concept that depicts five worlds with different socio-economic characteristics[36]. The population[37] and GDP[38] projections associated with the five SSP worlds are also shown in Figure 2-1 to compare the values that modeling studies (ones that meet below 2 °C target) are using against what is available in the SSP database[39]. The effects of SSPs on DACCS deployment are analyzed below in Section 2.3.1 in more detail.

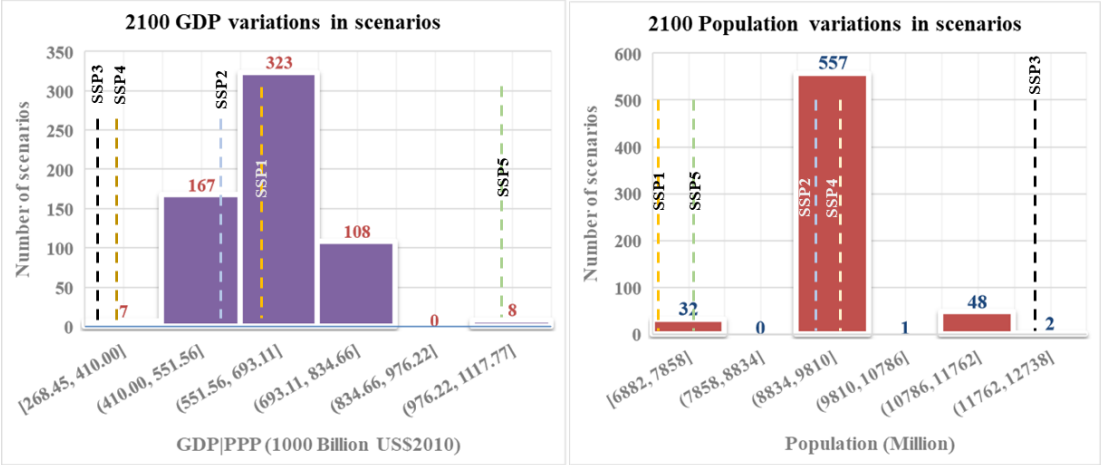

Figure 2-1. Distribution of GDP|PPP and population among AR6 deep mitigation scenarios (data from the IIASA AR6[25] and the SSP database[37–39])

In addition to the future's socio-economic characteristics, energy-related techno-economic factors increase or decrease the need for CDR. Models might use these factors as constraints (e.g., the potential for biomass energy) or assumptions (e.g., the future cost of renewable energy technologies), ultimately affecting CDR deployment. Since the models' inputs (assumptions and constraints) are not available in the AR6 database, we use the outputs as proxies to extract high-level insights from scenarios in the database. We limited this analysis to 212 scenarios meeting the 1.5°C end-of-century target (C1 and C2 categories) to exclude the changes that differences in the remaining carbon budget might imply. We also include data for non-biomass renewable and fossil fuel energy supply and final energy demand for

comparison. Since the estimates of CO_2 sequestered specifically by AR is not available for many scenarios (though it is embedded in the Agriculture, Forestry, and Other Land Use or AFOLU emissions), BECCS, DACCS and enhanced weathering are used to calculate the CDR deployment. Based on the distribution of cumulative CDR deployment (2050-2100), two groups of scenarios with high (equal to or above the 75th quantile) and low (equal to or lower than the 25th quantile) CDR deployment are determined. Figure 2-2 shows how these two groups vary regarding the final energy demand, energy supply by fossil fuels and renewables, and probability of temperature overshoot.

Among the aforementioned scenario factors that might drive differences in projections for cumulative CDR deployment, only projections of fossil fuel energy supply show a clear difference. Scenarios with low CDR deployment show a higher pace of transition from fossil fuels, which is in line with previous studies that show having CDR in the model on a large scale lessens the burdens of transition costs and decelerates the shift from fossil fuels[30,32,40]. The uncertainty range for the interactions of non-biomass renewables and CDR deployment is high because these two sectors might have two possible synergies depending on the CDR method that contributes most to the total CDR deployment. For example, in the case of BECCS, as it also provides energy in addition to carbon removal, we might anticipate that a high deployment of it decreases the need for non-biomass renewables. In contrast, DACCS, as an energy-intensive technology, might need a higher share of renewables in the energy system to reduce the carbon emitted in the energy supply process[41,42].

While most models assume a rise in energy demand and try to supply it, some studies focus on the demand side of the equation by producing narratives supporting future low-energy demand pathways that emit less GHG and therefore do not rely on CDR significantly[43,44]. It should be noted that since scenarios are from different modeling studies, there might be various techno-economic assumptions behind models that also contribute to the significant ranges of uncertainty shown in Figure 2-2, which will be discussed further below in 2.4.4.

Narrowing down our analysis to DACCS, we find that out of the 700 deep mitigation scenarios, only 254 scenarios had DACCS as an option. One of the reasons behind the underrepresentation of DACCS in scenarios meeting targets below 2°C (C1, C2, C3 and C4 categories) in the AR6 database is the fact that DACCS is a relatively new technology (compared to BECCS) and not an option in 6 out of 20 global models used to produce the AR6[25,45]. In addition, there are 189 scenarios in which models had DACCS as an option but were not considered (i.e., activated as an option) in the modeling exercise. In contrast, BECCS has been demonstrated in more than 94% of scenarios. Not having DACCS as a CDR option in many deep mitigation scenarios leads to higher estimates of other CDR methods, such as BECCS[46,47]. Figure A1 of Appendix A shows how the statistics of BECCS deployment in 2100 vary in

scenarios with DACCS as an option compared to those without DACCS. When scenarios do not include DACCS, the median and average values of BECCS deployment will increase from 8 and 9.6 Gt $CO_2/year_{2100}$ to 9.6 and 10.2 Gt $CO_2/year_{2100}$.

A high amount of BECCS deployment, however, might be infeasible or impose severe negative impacts on food prices and biodiversity[46,47]. This concern justifies the need to model possible CDR methods with realistic assumptions and reasonably precautionary limitations to avoid unrealistic representations. Yet, we found that many AR6 scenarios over-rely on BECCS and AR to meet climate change targets. We illustrate this problem by comparing projections in the AR6 database with the sustainable potentials of each CDR method provided by Fuss et al.[13] who estimated the sustainable deployment potential of different net-negative emission technologies (NETs) concerning their costs; impacts on socio-economic, environmental, and biophysical sectors; and the permanency of sequestration. Plausible sustainable deployment potentials were found for BECCS (0.5 to 5 $GtCO_2$/year) and AR (0.5 to 3.6 $GtCO_2$/year), limited mainly by land availability considerations and biodiversity losses. Using the upper deployment estimations of these two technologies (5 and 3.6 $GtCO_2$/year for BECCS and AR, respectively), we found that most of the 1.5 °C scenarios (C1 and C2 categories from the AR6 database) exceed this threshold. Figure 2-3 represents both the sustainable potential thresholds[13] and the AR6[25] modeling results. More than 60% and 85% of scenarios have exceeded the sustainable potential deployment thresholds of AR and BECCS.

Fuss et al.[13] also provided the potential for DACCS deployment in 2050 (0.5 to 5 $GtCO_2$/year), which was limited by its costs, current storage challenges and potentially unexpected environmental consequences. Importantly, they also determined that if current storage challenges and/or environmental concerns were to be addressed, DACCS might be able to remove up to 40 $GtCO_2$/year in 2100[13]. Regarding the sustainability implications of CDR methods, Honneger et al.[14] assessed the impacts of different CDR methods on the relevant sustainable development goals (SDGs). They found the high costs and energy requirements associated with DACCS as the factors dominating the effects of this technology on SDGs which could also limit its deployment potential. They discussed how siting decisions (e.g., deploying DACCS in areas with available waste heat) could alleviate the possible energy-related negative impacts of DACCS on SDGs[14].

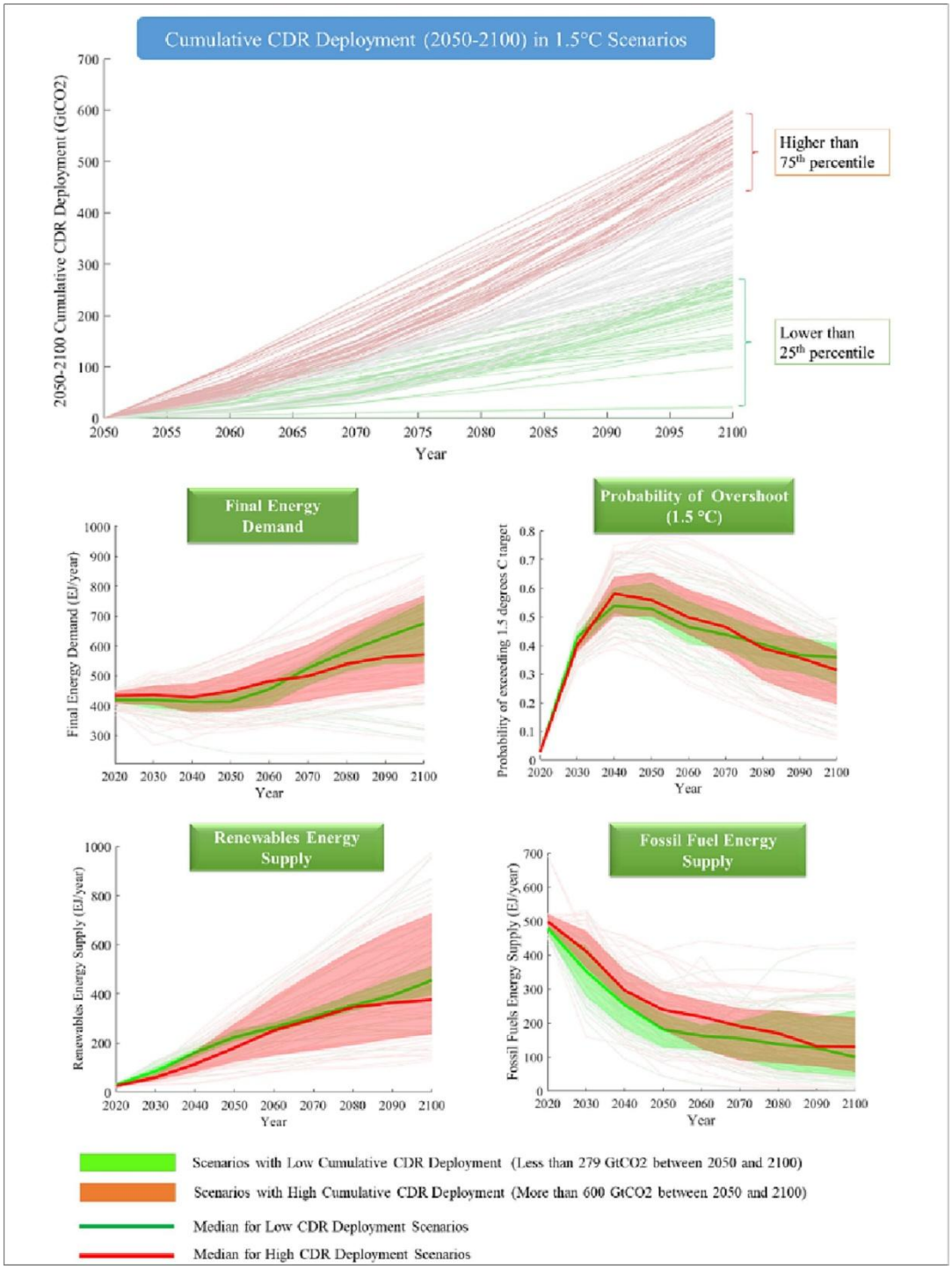

Figure 2-2. A comparison of 1.5 °C scenarios (C1 and C2) with high (above 600 $GtCO_2$) and low (lower than 279 $GtCO_2$) CDR deployment in the second half of the century

As we discussed, the availability of DACCS seems to reduce the reliance on BECCS (also shown in Fig A1 of Appendix A). These types of inter-method synergies are not limited to DACCS and

BECCS, and that is why studies suggest modeling a rich portfolio of CDR technologies [48–50]. DACCS can also be influenced in the same way by the introduction of new carbon removal methods to models. The extent of this effect depends on various factors, such as the cost of the method, its potential, and the permanency of carbon sequestration [13]. Since five models in AR6 did not have AR as an available CDR method, we could analyze the changes in DACCS deployment between scenarios with AR and those without it. Statistically, we found that the median value of cumulative DACCS deployment in scenarios with AR as an option is lower (around 70%) than those without AR (Figure A2 of Appendix-A). Accurate and more reliable insights on the effects of technology portfolio diversity on DACCS deployment would benefit from a multi-scenario analysis within the same modeling structure (e.g., one model run including AR and one model run excluding AR). We discuss the advantages of such studies in Section 2.4.4.

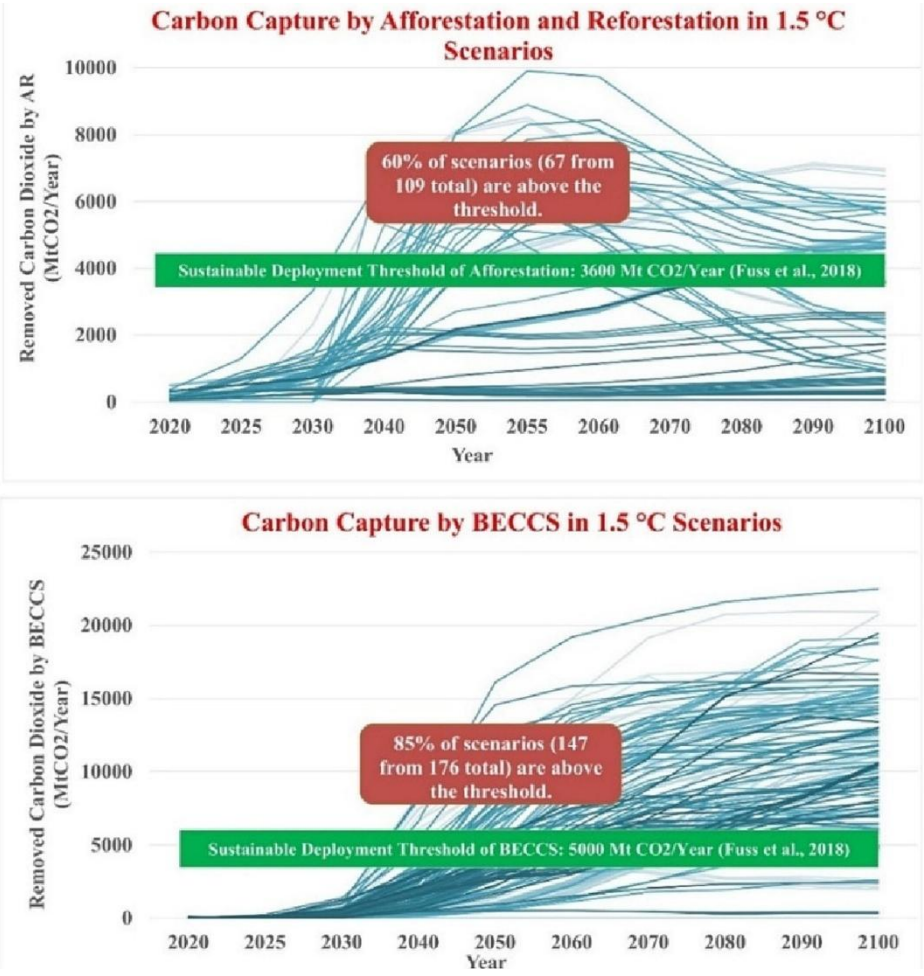

Figure 2-3. AR and BECCS deployment in 1.5 °C scenarios (C1 and C2 categories) of the AR6 database compared to the sustainable potentials suggested by Fuss et al.[61]

2.3 Key uncertainties affecting projections of direct air capture deployment under different IAM studies

Since the AR6 database does not provide full information on the underlying assumptions informing the scenarios, we identified nine peer-reviewed studies that generated DACCS scenarios that met the Paris targets. There is a high degree of overlap between the scenarios, including in the AR6 database and the chosen studies, with one study, Realmonte et al.[28], not part of the AR6 scenarios database. The objectives and critical findings from each study are summarized in Table 2-3. Within these studies, we identified 54 scenarios for analysis. The key attributes of each scenario analyzed are described in Table 2-4. Across the scenarios, deployment pathways for DACCS reflect significant differences in scale (between 0 and 38 $GTCO_2/year_{2100)}$ and deployment time. Comparing scenarios that differ in relation to a key variable allowed us to track the influence of these factors on DACCS deployment patterns.

We classify the elements affecting DACCS deployment into change categories shown in Table 2-5. The variations of DACCS deployment from one scenario to another are only due to the changes stated in the "category of change" column, which was found by comparing the scenarios in each study among themselves (not with scenarios from other studies). Overall, we can attribute the observed uncertainties to four clusters 1) socio-economic futures: different socio-economic narratives that can shape future society and their corresponding greenhouse gas emission activity[36], 2) intergenerational assumptions: stringency of mitigation target, permitted temperature overshoot level and social discount 3) maximum capacity and growth rate limitations: whether there is a limit on CDR/DAC deployment and 4) costs of DAC: Both current and future costs of the technology. The subsections below discuss these factors and their importance in DACCS/CDR modeling exercises.

2.3.1 Uncertainties regarding socio-economic futures

Depending on how the future unfolds over the coming decades, the world may have characteristics that facilitate or hinder the deployment of varying CDR methods. Here "the future" broadly refers to portfolios of socio-economic uncertainties, including population growth rates, economic growth, energy demand, energy supply, and political priorities. In climate change research, the global SSPs package five alternative futures that can be used to explore their potential effects on CDR deployment and DACCS[51]. The SSPs contrast different levels of socio-economic challenges to mitigation and adaptation. The variation between challenges results from differences in combinations of underlying assumptions for megatrends of scenario drivers such as population and gross domestic product (shown in Figure 2-1), education, technological development, and attitudes toward prioritizing sustainability[52,53].

Table 2-3. Reviewed integrated assessment modeling studies

Study	Goal and Insights
Marcucci et al. (2017)	• Investigation of the role of DACCS in meeting the PA targets and their effects on the energy transition and other system demands. • Recognition of DACCS as an essential technology in making the achievement of 1.5 °C possible and reducing mitigation costs. • The deployment projections are 38.2 $GtCO_2/year_{2100}$ for 1.5 °C and 21.3 $GtCO_2/year_{2100}$ for 2 °C scenarios.
Holz et al. (2018)	• Evaluating the role of CDR in achieving the 1.5 °C target and its trade-offs with stringent emissions reduction. • Emphasizing the significance of enhancing near-term emissions reductions of pre-2030 NDC targets. • Highlighting the issue of intergenerational equity by examining the implications of incorporating CDR in reducing near-term ambitions. • Projecting the deployment of DACCS at approximately 3.5 $GtCO_2/year_{2100}$.
Strefler et al. (2018)	• Assessment of different scenarios with varying temperature targets (1.5 and 2 °C) and limitations on total CDR deployment (e.g., 8, 12 and 20 $GtCO_2$/year). • The rising transitional challenges of the economy and energy sector when total CDR is less than 5 $GtCO_2$/year. • The need for at least 8 $GtCO_2$/year CDR to meet 1.5 ◦C target and more than 15$GtCO_2$/year to keep transitional challenges manageable. • A significant variation of DACCS deployment from 0 to 10.8 GtCO2 depending on the temperature target and limitations on total CDR.
Realmonte et al. (2019)	• The uncertainties associated with biological CDR methods and the need to consider other methods, such as DACCS, to meet the PA targets. • Investigating the role of DACCS under different cost estimates, energy requirements, maximum capacity ($GtCO_2$/year) assumptions, and growth rates (%). • Temperature overshoot of up to 0.8°C in case of relying on DACCS without subsequent deployment. • A projection of DACCS deployment around 30 and 28 $GtCO_2/year_{2100}$ to achieve a goal of 1.5 and 2 °C targets, respectively.
Fuhrman et al. (2020)	• Investigation of the role of DACCS in meeting the 1.5 target and its implications for food, water, and energy systems. • Introducing DACCS into models to some extent reduces the rate of increase in food prices compared to those scenarios relying only on BECCS and AR. • Highlighting the need for an urgent reduction in emissions to avoid the adverse land-water-energy effects introduced by the large-scale deployment of CDR methods. • DACCS deployment from 10 to 29 $GtCO_2/year_{2100}$, depending on its future cost trajectory and permitted overshoot level.
Fuhrman et al. (2021)	• Investigation of DACCS role under different shared socio-economic pathways (SSPs) in meeting the 2 and 1.5 °C goals. • The possibility of a high deployment of DACCS, especially when climate policies are delayed or significant challenges in mitigating emissions exist. • Depending on the socio-economic trajectory and the temperature target, DACCS might play a role from 0.03 to 31 $GtCO_2/year_{2100}$.
Grant et al. (2021),	• Modeling and analyzing the phenomenon of mitigation deterrence where the high future deployment of CDR in models dilutes near-term mitigation actions. • Highlighting the benefits of separating CDR and emissions reduction targets in climate strategies. • A projection of CO_2 removal by DACCS in the range of 10.1 to 20.53 $GtCO2/year_{2100}$.
Strefler et al. (2021a)	• Investigating the effects of different carbon pricing mechanisms on CDR deployment under 1.5 and 2°C goals. • Highlighting that alternative carbon prices can reduce long-term economic efforts, limit the total CDR deployment and be more implementable. • The varying range of DACCS deployment in 2100 from 21.3 $MtCO_2$ to 7.55 $GtCO_2$, depending on the carbon price trajectory and temperature target.
Strefler et al. (2021b)	• Investigating a comprehensive portfolio of CDR methods to compare transitional challenges (the pace at which emissions decrease) and economic efficiency (GDP loss). • The association of lowest transitional challenges with scenarios, including all CDR methods. • Range of DACCS deployment between 1.4 to 23 $MtCO_2/year_{2100}$ depending on the temperature target.

Table 2-4. Scenarios including DACCS selected from peer-reviewed studies for further analysis and their DACCS-related characteristics

Study	Integrated Assessment Model	Scenario Number	2100 Temperature Target and Oversoot Level	Socioeconomic		DAC growth rate limit (%/year)	Constraint (Gt CO2/year)	Direct air Capture characteristics				DACCS Deployment (MtCO2/year)			Cumulative DACCS Deployment (GtCO2)*
				SSP	Discount Rate			DAC Technology Variants	Cost of DAC ($/tCO2)	Heat GJ/tCO2	Electricity GJ/tCO2	2050	2080	2100	
Marcucci et al. (2017)	MERGE-ETL 6.0	S1	1.5°C	SSP2	5.0%	NF	NF	HT-DAC	600-200	8.1 -5.5	1.8	0.00	10889.70	38259.10	579.17
		S2	2°C		5.0%	NF						0.00	5413.50	21363.50	305.16
Holz et al. (2018)	C-ROADS-5.005	S3	1.5°C	SSP2	NF	NF	2.5 (for each of BECCS, Biochar, Mineralization); 3.5 (DAC)	NF				1668.56	3349.52	3480.11	163.95
	En-ROADS-96	S4		SSP2		NF						1662.35	3343.31	3478.68	163.53
Strefler et al. (2018)	REMIND 1.7	S5		SSP2	5.0%	NF	12 (CDR)	HT-DAC	102.5	10	2	0.19	833.38	3549.23	47.60
		S6				NF	20 (CDR)					1414.55	8393.57	10779.25	361.30
		S7				NF	8 (CDR)					1.34	75.13	2110.03	21.80
		S8	2°C			NF	12 (CDR)					0.00	107.46	1281.90	12.39
		S9	2°C			NF	20 (CDR)					97.52	7371.16	9284.92	255.20
		S10	2°C			NF	8 (CDR)					0.00	0.00	0.00	0.00
Realmonte et al. (2019)	TIAM-Grantham	S11	1.5°C	SSP2	5.0%	20.0%	30 (DAC)-10 (BECCS)	LT-DAC (DAC1) and two HT-DACCS: DAC2 (supplied by waste heat) and DAC21 (heat made on purpose)	DAC1: 300 -100 DAC2/21: 350-50	DAC1: 8.1 DAC2/21: 7.2	DAC1: 1.8 DAC2/21: 1.2	NF			~870
	WITCH	S12	1.5°C	SSP2	3.5%	20.0%									~822
	TIAM-Grantham	S13	2°C	SSP2	5.0%	20.0%									~756
	WITCH	S14	2°C	SSP2	3.5%	20.0%									~812
	TIAM-Grantham	S15	1.5°C	SSP2	5.0%	15.0%	3 (DAC) -10 (BECCS)								~100
		S16	1.5°C	SSP2	5.0%	20.0%									~125
		S17	1.5°C	SSP2	5.0%	30.0%									~140
		S18	1.5°C	SSP2	5.0%	15.0%	30 (DAC)-10 (BECCS)								~380
		S19	1.5°C	SSP2	5.0%	30.0%									~1030
		S20	1.5°C	SSP2	5.0%	20.0%			DAC1: 180-100 DAC2/21: 200-50						~880
		S21	1.5°C	SSP2	0.1%	20.0%			DAC1: 300 -100 and DAC2/21: 350-50						~750
		S22	1.5°C	SSP2	5.0%	20.0%				DAC1: 5.3 DAC2/21: 4.4	DAC1: 1.3 DAC2/21: 0.6				~870
		S23	1.5°C	SSP2	5.0%	20.0%	30 (DAC)-10 (BECCS) +Limited Storage			DAC1: 8.1 DAC2/21: 7.2	DAC1: 1.8 DAC2/21: 1.2				~820
Fuhrman et al. (2020)	GCAM 5.2	S24	1.5°C (High Overshoot)	SSP2	3.00%	NF	NF	HT-DAC	300	8.1	1.8	5685.30	21101.32	23291.35	863.00
		S25	1.5°C (High Overshoot)	SSP2		NF	NF		180	5.3	1.3	12327.89	26779.84	29096.16	1274.95
		S26	1.5°C (Low Overshoot)	SSP2		NF	NF		300	8.1	1.8	5761.55	10015.87	10521.76	497.22
		S27	1.5°C (Low Overshoot)	SSP2		NF	NF		180	5.3	1.3	12029.55	15503.02	16137.06	883.39

~ For scenarios of S11 to S23, yearly DACCS deployment data was not available in the IIASA database, and the authors estimated them based on the figures and data available in the main text of the corresponding study.

NF: Information regarding this element was not found in the study.

Table 2-4 (Continued). Scenarios including DACCS selected from peer-reviewed studies for further analysis and their DACCS-related characteristics

Study	Integrated Assessment Model	Scenario Number	2100 Temperature Target	Socio-economic			Direct air Capture characteristics				DACCS Deployment (MtCO2/year)			Cumulative DACCS Deployment (GtCO2)
				SSP	Discount Rate	Carbon Price Path	DAC Technology Variants	Cost of DAC ($/tCO2)	Heat GJ/tCO2	Electricity GJ/tCO2	2050	2080	2100	
Strefler et al. (2021a)	REMIND 2.1	S28	1.5°C	SSP2	5.0%	GDP Growth Rate	HT-DAC	102.5	10	2	1970.33	3580.99	6110.32	162.16
		S29	1.5°C	SSP2	5.0%	Discount rate untill net zero and then constant		102.5	10	2	2.33	5940.10	7552.29	285.81
		S30	2°C	SSP2	5.0%			102.5	10	2	1042.92	583.43	2452.82	33.83
		S31	1.5°C	SSP2	5.0%	Linear (Endegenously) to meet the target		102.5	10	2	0.00	5178.80	7294.05	236.66
		S32	2°C	SSP2	5.0%			102.5	10	2	51.23	126.25	1410.31	13.67
		S33	1.5°C	SSP2	5.0%	Optimal		102.5	10	2	0.00	7.05	21.39	1.61
		S34	2°C	SSP2	5.0%	Optimal		102.5	10	2	0.00	0.96	8.39	0.11
Strefler et al. (2021b)	REMIND-MAgPIE 2.1-4.2	S35	1.5°C	SSP2	5.0%	Constant after 2045	HT-DAC	102.5	10	2	855.42	297.44	32.62	13.89
		S36	1.5°C	SSP1	5.0%			102.5	10	2	23.77	1.38	1.47	0.57
		S37	2°C	SSP2	5.0%	Optimal		102.5	10	2	1.88	1.56	1.47	0.10
Fuhrman et al. (2021)	GCAM 5.3	S38	2°C	SSP4	3.00%	Endegenously to meet the end-of-century target	1.HT-DAC (with natural gas) [DAC11]; 2. HT-DAC (fully electric) [DAC12];3. LT-DAC (electric heat pump) [DAC2]	DAC11: 296 DAC12: 384 DAC2: 402	DAC11: 5.3	DAC11: 1.3 DAC12: 5 DAC2: 2.5	0.45	30.00	30.00	3.35
		S39	2°C	SSP4	3.00%			DAC11: 185 DAC12: 186 DAC2: 235			68.98	8501.71	10590.64	260.71
		S40	1.5°C	SSP5	3.00%			DAC11: 78 DAC12: 101 DAC2: 137			11904.54	30422.17	30657.64	1458.17
		S41	2°C	SSP5	3.00%						4746.87	31248.17	31565.86	1251.30
		S42	1.5°C	SSP1	3.00%			DAC11: 296-185 DAC12: 384-186 DAC2: 402-235	DAC11: 8.1-5.3	DAC11: 1.3 DAC12: 5.5-5 DAC2: 2.5	395.65	3273.68	1815.59	128.28
		S43	2°C	SSP1	3.00%						10.58	1296.14	4612.53	86.59
		S44	2°C	SSP1	3.00%			DAC11: 296 DAC12: 384 DAC2: 402			0.02	2.13	33.63	0.43
		S45	2°C	SSP1	3.00%			DAC11: 78 DAC12: 101 DAC2: 137			171.96	7623.08	8076.18	243.64
		S46	2°C	SSP2	3.00%			DAC11: 185 DAC12: 186 DAC2: 235	DAC11: 5.3	DAC11: 1.3 DAC12: 5 DAC2: 2.5	247.47	9792.29	9475.86	338.24
		S47	1.5°C	SSP4	3.00%			DAC11: 78 DAC12: 101 DAC2: 137			4303.03	21486.02	17655.80	902.74
		S48	2°C	SSP4	3.00%						688.73	20635.53	21033.43	661.84
Grant et al. (2021)	TIAM-Grantham	S49	1.75 °C	SSP2	1.00%		HT-DAC (DAC1) and LT-DAC (DAC2)	DAC1: 300-100 DAC2: 350-50	DAC1: 8.1 DAC2: 7.2	DAC1: 1.8 DAC2: 1.2	15.19	1065.29	10177.08	118.37
		S50	1.75 °C	SSP2	3.00%						15.19	1065.29	20505.29	180.34
		S51	1.75 °C	SSP2	5.00%						15.19	1065.29	20531.20	180.38
		S52	2°C	SSP2	1.00%						15.19	1065.29	10112.71	117.99
		S53	2°C	SSP2	3.00%						15.19	1065.29	16571.45	156.62
		S54	2°C	SSP2	5.00%						0.00	1065.29	20483.43	179.93

Table 2-5. Factors affecting DACCS deployment in different IAM studies.

Category of Change	Shift in Scenario		Change in DACCS Deployment (%)	Category of Change	Shift in Scenario		Change in DACCS Deployment (%)
	From	To			From	To	
Change in future socio-economic pathway*	S35	S36	-95.90%	Decreased Discount Rate	S11	S21	-13.79%
	S46	S48	95.67%		S51	S50	-0.02%
	S41	S46	-72.97%		S51	S49	-34.38%
	S41	S43	-93.08%		S50	S49	-34.36%
	S43	S46	290.63%		S54	S53	-12.96%
	S40	S42	-91.20%		S53	S52	-24.67%
	S40	S47	-38.09%		S54	S52	-34.43%
	S42	S47	603.73%	Limited Total CDR	S6	S7	-93.97%
Increased temperature target	S1	S2	-47.31%		S6	S8	-96.57%
	S5	S8	-73.97%		S9	S8	-95.14%
	S6	S9	-29.37%		S9	S10	-100.00%
	S7	S10	-100.00%		S5	S7	-54.20%
	S11	S13	-13.10%		S8	S10	-100.00%
	S12	S14	-1.22%	Limited DACCS	S11	S16	-85.63%
	S33	S34	-93.15%	Decreased DACCS grwoth rate limit	S11	S18	-56.32%
	S31	S32	-94.22%		S19	S11	-15.53%
	S29	S30	-88.16%		S19	S18	-63.11%
	S35	S37	-99.29%		S17	S16	-10.71%
	S42	S43	-32.50%		S16	S15	-20.00%
	S40	S41	-14.19%	Reduced Cost of DACCS	S11	S20	1.15%
	S47	S48	-26.68%		S24	S25	47.73%
	S49	S52	-0.33%		S26	S27	77.67%
	S50	S53	-13.15%		S38	S39	7670.99%
	S51	S54	-0.25%		S44	S45	57140.09%
Decreased Overshoot	S24	S26	-42.38%	Change in Carbon Price Trajectory	S29	S28	-43.26%
	S25	S27	-30.71%		S29	S31	-17.20%
					S29	S33	-99.44%

* Changes in the shared socio-economic pathways (SSPs) for scenarios by Furhaman et al. (2021) also change the costs and energy requirements of DACCS.

Red and Green colour codes are indicating the the intensity (relative) of negative and positive changes in DACCS cumulative deployment.

SSPs affect DACCS deployment in two ways. First, total emissions vary among SSPs for baseline scenarios[39], which has implications for the different amounts of carbon removal that might be required. Second, some SSPs have attributes that lead to increased or decreased DACCS deployments. For example, the SSP1 world depicts a low-carbon and low-energy-demand economy with considerable progress in renewable energy. While the availability of low-carbon energy can be seen as an opportunity for DACCS to be deployed, people's attitudes toward carbon removal technology might be unfavorable. In SSP1, the priority is to meet sustainability goals through nature-based solutions rather than technological approaches such as DACCS[51]. Some of the characteristics of SSPs that might affect the scale of DACCS deployment are provided in Table A1 and A2 (in Appendix-A), which are collected from the article introducing the SSP narratives[53] and their scenario elements and five marker scenarios that quantify them with IAMs[54–58]. The SSPs and marker scenarios were developed to give modelers contrasting yet comparable parameterizations (or, in the cases of variables modeled endogenously, target outcomes) for alternative long-term worlds. When SSPs are utilized to project demand for DAC (or other CDR methods), modelers should consider the effects of alternative SSPs (e.g., differences in

policy environments) on the technology's costs, energy, and water requirements in addition to its maximum growth (e.g., due to tech-related characteristics and levels of social acceptance). Moreover, differences in factors such as international trade, globalization and technology transfer might have implications for the regional distribution of the technology that models project (see Table A1 of Appendix-A). As shown in Table 2-4 and Figure 1-1, in most of the IAM studies reviewed here, the role of different SSPs is missing, as most studies utilize assumptions for SSP2.

A notable contribution in this area is Fuhrman et al.[29]. They investigated the roles of different CDR methods under various SSPs in scenarios meeting 1.5 and 2 °C targets. In their analysis, many socio-economic and technological factors varied between SSPs, including timing and stringency differences of land-use and climate policy (i.e., carbon price), social acceptance of DACCS technologies (low for SSP1 and intermediate for SSP5; applied by varying the shares of global GDP assigned to DACCS), and energy and cost requirements of DACCS (both the initial value and future trends). Their model could not find any SSP2 pathway that could meet the 1.5 °C goal; also, for SSP3, meeting both 1.5 and 2 °C was impossible. For the 1.5 °C target, Fuhrman et al.[29] found that an SSP1 (sustainable development) world relies much less on negative emission technologies, and DACCS has a minimal role (1.8 $GtCO_2$/y in 2100). On the other hand, in a world like SSP5, with high energy demand and high fossil fuel combustion, the DACCS role will increase to 30 $GtCO_2$/y in 2050[29]. The variations between the DACCS deployment rate among different SSPs highlight the importance of incorporating socio-economic scenario uncertainty in the modeling process. Having a lower DACCS deployment scenario under an SSP1 future is also shown in the results of Strefler et al.[33], where DACCS deployment decreases from 32.6 (S35) to 1.4 Mt $CO_2/year_{2100}$ (S36) when shifting from the SSP2 to SSP1 scenario[33]. It should be noted that Strefler et al.[27] also did a sensitivity analysis on SSPs by comparing the SSP2 scenarios with SSP1 and SSP5 futures. These particular scenarios are not available in the IIASA database, but their graphical results are provided in their peer-reviewed study[27].

2.3.2 Intergenerational Assumptions: Time Value of Costs and Appetite for Overshoot

Another key factor determining how much DACCS (and other CDR methods) will be deployed is the timing and level of ambition that scenarios are trying to meet. Such characteristics reflect intergenerational assumptions and affect whether and how much overshoot (and, in turn, DACCS deployment) is acceptable. The social (intergenerational) discount rate (SDR) is applied to future benefits and costs to calculate net present values[59]. The value of the SDR is a critical parameter in determining the deployment scale of DACCS and other CDR methods. Higher values of SDR in the context of climate change policy-making discount the costs of climate action and the impacts of climate change on future generations, thus implying a lower amount of investment in emissions reductions and

CDR today. It should also be noted that multiple studies have looked at the SDR from an ethical perspective and discussed the appropriate selection of this value in cost-benefit analysis when intergenerational assets are involved, and topics such as intergenerational equity have been raised[59–62]. In 2015, more than 200 economists participated in a survey recommending what SDR is ethical and reasonable to use in climate change studies. Over 90% of them found SDR values between 1 and 3% acceptable[63]. In the studies that we analyzed in this article, there are very different assumptions regarding the SDR. Marcucci et al.[26], Strefler et al.[27] and Strefler et al.[33] use 5%. Realmonte et al.[28] changed the SDR from 5% to 0.1%, making the cumulative DACCS deployment fall from 870 to 750 $GtCO_2$[28]. Fuhrman et al.[29] used the SDR of 3%. Grant et al.[31] considered three scenarios of 1, 3 and 5% SDR and observed the decreasing effects of lower SDR values in CDR deployments. DACCS deployment (in 2100) was approximately doubled when SDR was set to 5% compared to the initial value of 1% both for 1.75 and 2 °C scenarios. In addition to the effects of SDR changes on CDR deployment, their results also show that using higher SDR values leads to higher 2030 CO_2 emissions, lower yearly mitigation investments, lower renewables deployment, lower energy demand reduction in 2030 and a higher share of fossil fuel in 2030 final energy[64].

In many scenarios, it is contemplated that temperature rise will pass the threshold of 1.5 °C some years before 2100. Potentially, through applications of CDR, the change in global average temperature could be returned to below 1.5 °C at the end of the century—a phenomenon referred to as the "overshoot" of the global temperature goal. Due to the risks associated with triggering tipping points or irreversible climate change impacts caused by passing 1.5 °C[66–71], limiting the magnitude and duration of overshoot as much as possible[72] is advisable. Preventing the model from experiencing overshoot (especially for the 1.5 °C goal) will increase mitigation costs and require higher rates of emissions reductions with less CDR[3]. CDR methods can, at best, compensate for emissions released over the remaining carbon budget, but they cannot alleviate the burdens of irreversible biophysical changes. Fuhrman et al.[18] investigated restricting overshoot (from high to low) for two high and low-cost scenarios (S24 and S25, respectively). By constraining global CO_2 emissions pathways, they derived two global warming trajectories of (1) high-overshoot and (2) low-overshoot, both meeting the end-of-century temperature target of 1.5 °C. The former will experience a global warming level of 1.78 °C in 2055, followed by a rapid decline till 2100. In the latter, the peak temperature is 1.56 °C, which occurs in 2045, and the end-of-century warning level is 1.32 °C. When changing the condition from high to low overshoot, they found a significant drop in the cumulative DACCS deployment (around 30% to 40% reduction)[18]. These changes are shown in the left columns of Table 5 for the category "Decreased Overshoot" when shifting scenarios from S24 to S26 and S25 to S27. Moreover, increasing the temperature target (e.g., from 1.5 to 2 °C) decreases the cumulative DACCS deployment in many

scenarios (see the left side of Table 2-5). Since the remaining carbon budget corresponding to a lower temperature target is also lower, models use more CDR to compensate for emissions. This result is also reflected in the median values of DACCS deployment in the AR6 database scenarios when moving from the C3 and C4 categories (2 °C) to C1 and C2 (1.5 °C), as summarized in Table 2-2.

2.3.3 Maximum Capacity and Growth Rate Limitations

Some models set limits on CDR/DACCS deployment to avoid models over-relying on such strategies to compensate for the lack of more proven mitigation strategies. This issue is crucial for BECCS and AR, which might threaten sustainability goals when deployed at large scales (Figure 2-3). In the peer-reviewed IAM studies examined for this article, Holz et al.[30] used 50% of the potential of different CDR methods, assumed by En-ROADS and C-ROADS, as limits. This corresponds to 2.5 $GtCO_2$/year and 3.5 $GtCO_2$/year for BECCS and DACCS, respectively. Strefler et al.[27] released the results of CDR deployment in six scenarios consisting of different combinations of two temperature targets of 2 and 1.5 °C and three upper limitations on yearly total CDR deployment of 8, 12 and 20 $GtCO_2$. For 1.5 °C scenarios, the DACCS deployment rates in 2100 were 2.1 (S7), 3.5 (S5) and 10.7 (S6) $GtCO_2/year_{2100}$ for 8, 12 and 20 $GtCO_2$/year maximum CDR deployment, respectively[27](shown in Table 2-4). This means that even limiting the total CDR deployment to 8 $GtCO_2$, at least 25% of the removed carbon comes from DACCS, which could be a proper conservative estimate of possible DACCS deployment in 1.5 °C scenarios. However, when the temperature target is 2 °C, and there is an 8 $GtCO_2$/year limit on the total CDR deployment, DACCS will not be deployed (S10)[27]. Realmonte et al.[28] assumed 10 Gt CO_2/year for BECCS deployment for all scenarios and investigated the DACCS deployment changes when its role is limited to 30 and 3 $GtCO_2$/year, corresponding to scaling the sorbent production market by a factor of 100 and 10, respectively. Their study also incorporated the constraints on the possible growth rate of DACCS to enhance the feasibility of their pathways [28]. Some studies criticize IAMs because of their infeasible speed of technological change[73]. This parameter might be hard to determine as it depends on various factors, such as modularity, political and economic incentives and public acceptance of DACCS, which could also vary for different SSPs. Realmonte et al.[28] used historical diffusion rates of various technologies, such as wind, solar, natural gas, and nuclear energy, and decided to use three values of 15, 20 (baseline) and 30% as growth rates that might apply to DACCS[28]. The significant impacts of these changes (decreased DACCS growth rate limit) on the DACCS cumulative deployment are shown in Table 2-5. Other IAM studies reviewed here have not analyzed the temporal deployment of DACCS, which is a crucial factor for producing pathways that might be more plausible and informative for real-world settings.

2.3.4 Non-Energy Costs of DACCS

DACCS deployment in IAMs is limited by its costs. The technology is not mature, and the cost estimations from techno-economic analyses and a limited number of commercial projects vary substantially. Such uncertainty makes reaching a consensus on the costs of DACCS very challenging. This has led some studies to do a sensitivity analysis of the costs associated with DACCS. Fuhrman et al.[18] investigated four different scenarios meeting 1.5 °C by combining two levels of overshoot (high and low) and costs of DACCS (high and low estimates from the literature). Fixing the overshoot variable shows that a decrease in unit costs from 300 $/tCO$_2$ to 180 $/tCO$_2$ increases the cumulative deployment of DACCS from 863 to 1274 GtCO$_2$ for high overshoot scenarios (S24 and S25) and from 497 to 883 GtCO$_2$ for low overshoot scenarios (S26 and S27). Realmonte et al.[28] also found that when the initial cost of DACCS changed from 300 to 180 $/tCO$_2$ for HT-DAC and 350 to 100 $/tCO$_2$ for LT-DAC, it increased the cumulative deployment rate by around 10 GtCO$_2$. Since the models and their other assumptions are different, it is hard to determine why the model used by Fuhrman et al.[18] showed more sensitivity compared to Realmonte et al.[28]. However, based on the available information, the model Realmonte et al.[28] developed has two prominent elements that might have contributed to their findings. First, they put an upper limit on DACCS deployment of 30 GtCO$_2$ (which was already reached even in the high-cost DACCS scenario). Second, the costs of DACCS in their model were not fixed, and they provided floor costs of DACCS, which were 100 (HT-DAC) and 50 $/tCO$_2$ (LT-DAC) for both high and low-cost scenarios[28]. Floor costs are the minimum cost the technology might achieve with the learning rate in the coming years. All the costs mentioned above exclude the energy costs enabling the model to incorporate it endogenously depending on the energy source cost trajectory[28,29]. For this reason, estimates of total costs are higher than the non-energy costs of DAC. For example, the International Energy Agency GHG estimates that the cost of first-of-a-kind DACCS technology ranges from $400 to $700 for a net removal of one tCO$_2$, incorporating the emissions of the energy source, using global average solar photovoltaics (PV)[74].

Another critical factor is how DACCS costs evolve, which depends on many uncertain socio-economic, technological, and political factors and the DACCS deployment[75]. While some IAM studies use a fixed cost for the simulation period, a group of studies has differentiated between the initial cost and the floor cost[26,28,29,76]. The numerical representation of the learning rate shows the percentage reduction of costs at each time step that the cumulative capacity doubles[77]. While the median learning rate of solar PV (photovoltaic) is 23% (from 1959 to 2011) and for onshore/offshore wind is 12% (from 1979 to 2010), much lower rates are observed in technologies such as geothermal, nuclear, and

hydroelectricity[78]. Predicting the learning rate for DACCS is a highly uncertain process. Fasihi et al.[79] used 10% and 15% values as the conservative and baseline estimates of the learning rate variable for DACCS[79]. These learning rates were derived from the literature on DACCS and similar technologies[80,81]. Finally, carbon pricing may also affect the scale of DACCS deployment due to path dependencies that might be introduced by cheaper CDR technologies (e.g., BECCS, enhanced weathering). This issue was examined in studies by Strefler et al.[27] and is discussed further in supplementary information (Figure A3 in Appendix-A).

2.4 Modeling recommendations to explore and better understand the scale and pace of direct air capture deployment

2.4.1 Regional Differences and the Need for Context-based Regional Scenarios

Across the scenarios reviewed for this article, there are significant regional differences in DACCS deployment, even for scenarios with the same SSP, temperature target and range of DACCS deployment. Figure 2-4 compares four scenarios of S1, S6, S26 and S27, respectively, removing 580, 361, 479 and 883 $GtCO_2$ by DACCS for the whole century. DACCS in the Middle East and North Africa provide 25% and 20% of total removals in the S1 (MERGE-ETL used by Marcucci et al.[26]) and S6 (REMIND model used by Strefler et al.[27]) scenarios, while no DACCS is being deployed in these regions in scenarios S26 and S27 (GCAM results by Fuhrman et al.[18]). Worldwide, current DAC pilot projects are in the developed economies of North American countries (by Carbon Engineering) and European countries such as Iceland and Switzerland (by Climeworks). A significant open question is how countries with fewer financial and technological resources, institutional capacity and political stability might deploy this expensive technology on the scales that some IAMs project. For this reason, *we recommend the integration of global IAMs with national analyses to deliver more realistic estimates of different pathways that might meet global climate change targets.*

Geographical differences might lead to different deployment pathways for DACCS and DACCU. Geological storage options and available capacity vary among regions. In addition to the availability of reservoirs, the economic and technical feasibility of storage, public acceptance[82], and regulatory frameworks might be in favor or against storage. Moreover, regional demand for CO_2 as a raw material and/or an international market for CO_2-based products may significantly promote DACCU in different regions[83].

Downscaled or extended SSP scenarios are appropriate tools for analyzing different climate mitigation, adaptation and CDR strategies and policies at national and sub-national levels[84,85]. Such scenarios can be valuable in different ways:

- Being informative for assessing different mitigation policies and leading to more reliable and realistic regional outcomes with varying characteristics of regions that may influence the performance and efficiency of CDR/DAC alternatives[84,86].
- Helping policy-makers analyze their mitigation goals or international pledges (such as nationally determined contributions reported to the United Nations based on the Paris Agreement) and facilitating pathways toward meeting their targets[87,88].

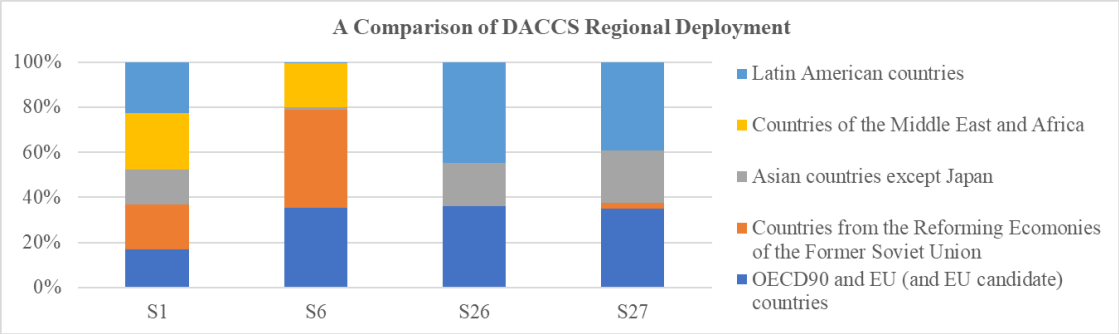

Figure 2-4. Variations in the regional deployment of DACCS among scenarios

2.4.2 Modeling both high-temperature (HT) and low-temperature (LT) DAC

In addition to the benefits of modeling different CDR methods and having a diverse CDR portfolio, having both HT-DAC and LT-DAC needs to be a more typical exercise among studies. Such considerations are important because the system demands of these two approaches vary significantly (shown in Table 2-1), which can, in turn, shape different temporal and spatial deployment pathways for them. While HT-DAC and LT-DAC are mature technologies proven to be techno-economically feasible, HT-DAC seems more mature, as it utilizes the technology and equipment used in other industries (namely pulp and paper)[28]. This could be the reason why many reviewed studies, such as Marcucci et al.[26], Holz et al.[30], Strefler et al.[27], Fuhrman et al.[18], and Strefler et al.[32,33] only incorporated HT-DAC. Three studies[28,29,64] reviewed in this paper (from a total of nine) considered both variants of DACCS. According to their results, *we recommend having both options available in models*. One of the critical differences between them is energy requirement. Since LT-DAC needs a relatively lower

temperature (around 80 to 120 °C) of heat energy compared to HT-DAC (above 800 °C), the required heat energy can be supplied from different sources, such as industrial low-grade waste heat, renewables, heat pumps and geothermal[22,79,89–92]. On the other hand, 800-900 °C thermal energy cannot be provided by using second-hand energy[90], which makes natural gas a desirable energy supply option.

In most of the scenarios in the study by Realmonte et al.[28], the LT-DAC contribution is higher than HT-DAC, probably due to the costs and energy requirements of HT-DAC (Table 2-1). They found that HT-DAC will be deployed later than LT-DAC because cheaper natural gas is anticipated to be available later in the century due to less fossil fuel being used for producing electricity (Realmonte et al.[28]). While in most of the scenarios of Fuhrman et al.[29], HT-DAC and LT-DAC were found to be deployed at the same scale (S46), there were other scenarios where either HT-DAC (S41, S47 and S48) or LT-DAC (S42 and S43) was the major DAC variant being deployed. These differences are driven in part by specific characteristics about alternative socio-economic futures. When renewables and nature-based solutions are favored and there is less dependency on fossil fuels (SSP1), LT-DAC has higher deployment. In such scenarios, renewables are available at lower costs, and since LT-DAC needs low-temperature heat energy, thermal energy for DAC can be produced by electric heat pumps. On the other hand, HT-DAC had a more significant role in scenarios corresponding to worlds with a higher reliance on fossil fuels (SSP4 and SSP5). This is because the high-temperature heat required for HT-DAC is provided by cheap natural gas with carbon capture and storage [29].

2.4.3 The necessity of considering both carbon utilization and storage pathways

Most IAM studies do not incorporate both CO_2 capture options of utilization and storage after deploying DAC technology. In DACCS, the captured CO_2 will be permanently sequestered in geological reservoirs; in DACCU, it will be utilized for different purposes, such as chemical feedstock (e.g., material and fuel synthesis) and injection fluid[23,24]. The implications of these two options for the carbon balance are very different. While introducing and advancing “clean fuels” is necessary for mitigating climate change by substituting fossil fuels, decarbonizing electricity, and reducing the need for a large amount of biomass with land-use problems[83], a DACCU system should not be considered “negative” from a carbon balance standpoint. Fuels produced using captured carbon can be, at best, carbon neutral due to emissions released during their use phase[23]. Studies that examined DACCU systems have primarily focused on life cycle assessments, techno-economic analysis and possible projections of the future role of DACCU. A good example can be a study by Akimoto et al.[24], where they analyzed the

complex interactions between DAC and utilization system (regarding the marginal abatement cost of CO_2) and projected a carbon utilization market of 1 $GtCO_2/year_{2100}$ in a scenario meeting a 1.5 °C target[24]. Since IAMs aim to model interactions between different economic, social and energy sectors and can incorporate various shared socio-economic uncertainties, *we recommend that IAM studies explore how the temporal and spatial deployment of DACCU and DACCS might materialize under different climate change targets, SSPs, assumptions regarding carbon utilization markets, and costs of technologies*.

Furthermore, DACCS deployment is only possible if a government policy regarding emissions reduction or carbon removal (e.g., carbon tax, cap-and-trade system) is in place. A carbon utilization market would alleviate the dependency of DACCS on government policy[93]. Moreover, the availability of DACCU in the early stages of DAC deployment decreases the burdens of high contemporary costs of DAC technology, providing an opportunity for early projects to grow faster and allowing for economies of scale to reduce costs via learning-by-doing[75]. We can also see that various companies, such as Climeworks, Carbon Engineering and Global Thermostat, are deploying DACCU or have plans for demonstration projects[94]. This observation also highlights the necessity for models to consider utilization pathways of the captured carbon by DAC.

Finally, because the current level of carbon storage is negligible and might lack public support and regulatory frameworks, we recommend that IAM studies use conservative estimates of regional available geological storage and/or perform sensitivity analysis on this parameter.

2.4.4 Differences between models, underlying assumptions, and the need for model intercomparison projects

IAMs explore the interactions between social and natural systems to assist policy-makers, provide insights for the general public, and contribute to scientific analysis[95,96]. While these models can help assess the impacts of different policies or find pathways to meet specific targets, a lack of transparency in communicating modeled assumptions and uncertainties or not having the proper knowledge to interpret the results can be misleading. *We recommend that modeling studies should be transparent about the underlying assumptions that affect DACCS deployment and that multi-model assessments be produced (e.g., model intercomparison projects) to analyze the robustness of results, making them valuable for policy-making.*

The results for DAC deployment of different modeling activities vary significantly, even when they try to model pathways to the same target (e.g., scenarios meeting 1.5 °C) or assess the effects of the same policies (e.g., studies that explore the outcomes of countries' pledges). We showed DACCS deployment covers a wide range between the cumulative deployment of 0.4 $GtCO_2$ to around 1200 $GtCO_2$ (in scenarios that meet the 1.5 C° target). The reason behind this variation can be classified into two categories: 1) research objectives (e.g., modeling pathways with low energy demand) and their underlying assumptions[97] and 2) differences in the structures of the IAMs[98,99].

Most of our focus in this paper was on modeling assumptions, but we also discussed some issues regarding the structure of the model (see different CDR methods presented in models in Section 4.2). Being transparent about the modeling assumptions and the research objectives can help address and interpret this source of uncertainty. Due to the various modeling assumptions and structures employed, comparing the results from different modeling exercises to completely characterize the causal relations between the drivers of a specific scenario or model element and the modeled outcomes is impossible. For scenarios reviewed here, Fig A4 (in the supplementary information) summarizes the differences between various projected energy sources and projected final energy demand variations. Among SSP2 pathways that meet 1.5 °C, we see scenarios heavily relying on nuclear, coal, oil and gas energy supply in 2100 (S24 to S27 by Fuhrman et al.[18]), and others showing a significant expansion of renewables such as wind, hydro, geothermal and solar (S28 to S24). As discussed previously, such differences will also affect how much CDR/DACCS is required as well as the distribution of HT- and LT-DAC.

A proposal for enabling the inter-comparison of DAC projections among different IAMs is "harmonization" [100] which should include socio-economic assumptions, techno-economic assumptions, economic aspects related to fossil fuel prices, and climate-related implementation policies[97]. We believe the SSP family scenarios have successfully addressed many of these issues, specifically for socio-economic assumptions, and provided a comprehensive, qualitative picture of other aspects[101]. However, studies mostly use only their quantification schemes due to a lack of more specific guidelines regarding model implementation.

The impacts of IAM structure on the modeling results can only be assessed when the modelers have set homogenous assumptions (to the level that structure allows) among models. This is where inter-model comparison studies can be conducted, which could be valuable for enhancing the robustness of results[99]. IAMs might differ in various aspects, such as the representation of energy technology details

(also regional distribution), sectoral supply and demand details, availability of mitigation options, incorporation of land use, the inclusion of macroeconomic feedback and type of solution algorithm[95,98,99]. Some studies have investigated the impacts of IAMs' structural differences on specific outcomes, such as BECCS deployment[102] and food security[103] in mitigation scenarios, and have found significant variations in their results. Regarding DACCS, Realmonte et al.[28] have investigated such effects by analyzing DACCS deployment with two models: TIAM-Grantham[104] and WITCH[105]. Their results of cumulative DACCS deployment for both models were in the same range for baseline scenarios. However, more variations in DACCS deployment were observed in some of the sensitivity analysis scenarios. Additionally, the electricity energy mix (contribution of different sources) and BECCS and AR deployment are pretty diverse among the models (shown in the supplementary figure A4 of Realmonte et al.[28]), further illustrating the impact of model structure on outcomes.

2.5 Discussion and Conclusion

This article focused on IAM projections of DACCS and discussed the nuances behind significant variations of its deployment pathways in different scenarios to achieving Paris Agreement targets. We investigated the IPCC AR6 database in addition to a more in-depth analysis of 54 IAM scenarios published in the peer-reviewed literature modeling DACCS[18,26–33]. We began by noting that two technological variants of DAC, HT and LT, have significantly different resource demands for energy and water, so it is essential to explore how much DAC might be demanded to achieve Paris targets and how much resources DAC may require. Such questions are appropriate to explore with IAMs. We then investigated the IPCC AR6 database to see how well DAC was represented among scenarios that achieve Paris Agreement targets. DAC is covered in a minority of relevant AR6 scenarios (253 of 700).

Before drawing conclusions from the AR6 database scenarios for DAC, we examined the larger context of CDR demand in the scenarios. Amongst various scenario factors that might matter for differences in CDR deployment, we observed that fossil fuel energy supply was the only factor that distinguished scenarios with low cumulative CDR from high cumulative CDR. We also found that a majority of AR6 database scenarios deploy AR and BECCS at levels that exceed sustainable deployment thresholds (60% of scenarios and 85% of scenarios, respectively). Such findings are concerning since a high reliance on land-intensive CDR methods such as BECCS has been controversial[47,106] because of its possible adverse effects on food availability and prices. From the AR6 database scenarios that include DACCS, we found a reduction in the average (around 5%) and median

(around 15%) of BECCS deployment in scenarios with DACCS as an option (see Figure A1 in the supplementary information).

The AR6 scenario database only hosts the outputs of scenario studies, and the underlying assumptions (including study design and model structure) of IAM studies matter. We, therefore, consulted peer-reviewed studies of DACCS deployment to capture such dimensions that cannot be gleaned from the AR6 database alone[18,26–33]. Noteworthy factors were aggregated into four categories: 1) uncertainties regarding socio-economic futures (Section 2.3.1), 2) intergenerational assumptions (Section 2.3.2), 3) maximum capacity and growth rate limitations (Section 2.3.3) and 4) costs of DACCS (Section 2.3.4). Table 2-5 summarizes our key findings.

First, with respect to socio-economic assumptions, we found that most scenarios (41 out of 49 reviewed here) use the assumptions of SSP2, even though DACCS deployment will significantly change under different SSPs. For example, with a shift from SSP1 to SSP4 (e.g. a shift from S42 to S47), DACCS deployment increases by around 600%. This example can be found in Table 5 for the category "change in the future socio-economic pathway". The elements deriving these behavioral changes in models include but are not limited to demographic characteristics (e.g., GDP and population projections as summarized in Figure 2-1), technological change and innovation trends, and the level of respect toward environmental boundaries[101]. As there is no guarantee of what path the world will choose for the rest of the century, conducting studies assessing DACCS (or other mitigation policies) under various levels of socio-economic challenges embodied in the narratives of different SSPs would be helpful.

Second, regarding intergenerational assumptions, temperature targets and overshoot levels affect DACCS deployment as summarized in Table 2-5. For the categories "increased temperature target" or "decreased overshoot" level the need for DACCS may be significantly reduced. In some scenarios, a change in temperature target from 1.5 to 2 °C reduces DACCS deployment by -100% (e.g., a shift from S7 to S10), which means DACCS is not being deployed anymore. Another important factor is the social discount rate (SDR), which is an economic parameter that models use to estimate the present value of future costs and benefits. This variable is essential in determining the stringency of near-term climate change actions and the level of DACCS/CDR needed in the late century. In the category "decreased discount rate", we see some shifts in scenarios that lead to reductions of up to 35% in DACCS

deployment when an SDR of 5% (applied in scenarios S54 and S51) changes to 1% (applied in scenarios S52 and S49).

Third, when models limit the yearly deployment of total CDR or specific methods, such as BECCS and DACCS, their deployment pathways will change. For the category "limited total CDR", there is a 100% reduction in DACCS deployment when the limit on CDR decreases from 20 to 8 $GtCO_2$/year (e.g., a shift from S8 to S10). Another factor missing in most studies is the growth rate limit that constrains the annual pace at which DACCS deployment can be increased. Table 2-5 shows "decreased DACCS growth rate limit" can reduce DACCS deployment by 56% when the growth rate limit decreases from 20 to 15 % per year (S11 to S18).

Fourth, there is an extensive range of cost estimates for DACCS used across models, which shows a lack of consensus on both the current and future costs of this technology. By looking at the category of "reduced costs of DACCS" in Table 2-5, we can observe in most cases a significant increase in DACCS deployment as a result of decreased costs (costs are shown in Table 2-4). In some cases, DACCS cumulative deployment increases by about 500 times when costs fall by a factor of three (a shift from S44 to S45). Considering the uncertainty around the current cost estimates of DACCS and the future demand for the technology, models are encouraged to do sensitivity analysis around costs to capture this source of uncertainty.

After examining how various modeling assumptions lead to significant variations in projections of DACCS, we also made four recommendations for how IAMs might produce pathways that would be more informative for real-world settings. First, we noted that the projected regional deployment rates of DACCS among models (Figure 2-4) are not uniform, so there is also variation in the possible spatial contribution of DACCS globally. To provide policy-relevant insights to national governments, we recommend integrating national/regional perspectives with global IAMs to enhance the feasibility of scenarios.

Second, we reiterated that the system demands of HT-DAC and LT-DAC vary significantly (shown in Table 2-1), which justifies the need for considering both variants in modeling studies. However, we found only two IAM studies[28,29] that investigated the implications of having both variants of DACCS available as options. The studies suggest that LT-DAC would have higher deployment in worlds with socio-economic outcomes resembling SSP1, where there is less dependency on fossil fuels (including lower cumulative emissions) and renewables make up a large share of the global energy supply.

Third, most IAM studies have not modeled CO_2 utilization after deploying DAC technology (i.e., DACCU). We discuss notable findings in the literature that suggest CO_2 utilization markets on the order of 1GtCO_2/year could be realized as early as 2050. Developments in DACCU are essential to the model because they might alleviate the dependency of DACCS on government policy and provide market incentives for reducing DAC costs via learning by doing.

Fourth, this review cannot provide definitive reasons for the changes in DACCS deployment among different IAM studies since not only do the scenario assumptions differ among studies but also the structures of the models are distinct (discussed in Section 2.4.4). We recommend that future studies investigate the roles of each source of uncertainty in DACCS deployment by analyzing harmonized scenarios under different models (so-called inter/multi-model comparison studies) to produce more robust results.

In addition to the uncertainties observable from the IAMs modeling DACCS, many scholars have criticized some aspects of IAMs that might also contribute to our discussion. These critics revolve around representing heterogeneous actors and aligning with behavioral realism[107–109], technology innovation, diffusion and dynamics[98,108], capital markets and finance[108], carbon pricing and its relationship with socio-technical transitions[108], energy-economy feedback[108], and consideration of ethics and justice[110,111].

While IAMs mostly rely on rational decision-making actors (maximizing the monetary utility), real-world decision-making is often more complex and may not conform to the rationality principles [109]. Billions of dollars in investments in DACCS and the significant role of voluntary markets that companies (early adopters) have shaped around the DACCS ecosystem[112] are examples of decisions which do not follow the traditional definition of rationality (agents select the least-price alternative).

While scientific evidence emphasizes the importance of decarbonization and transitioning to a low-carbon lifestyle, CDR methods models may overestimate their potential impact due to discounting future mitigation costs and neglecting hard-to-quantify behavioral changes (e.g., diet changes). This has led some researchers to recommend collaboration between ethicists and energy-economy modelers to reduce inherent risks and consider justice principles[110]. There is an equity-driven element to CDR and DACCS provision that also does not get reflected in IAMS. The Paris Agreement is informed by differentiated responsibilities framed as expectations that developed states will contribute to mitigation measures with greater ambition. However, the geographic distribution of CDR opportunities based on

biophysical capacities or least-cost models show different outcomes than scenarios that account for equitable considerations, such as the ability to pay or historical responsibility[113,114]. These concerns will be relevant to the trajectory of DACCS development.

Acknowledgment

This project was funded in part by the Government of Canada. The Government of Canada's Environmental Damages Fund provided funding for this project under its Climate Action and Awareness Fund. This work was also supported by NSERC Discovery Grant numbers RGPIN-2016-04157, held by Professor Vanessa Schweizer, and RGPIN-2018-04345, held by Professor Keith W. Hipel. Moreno-Cruz also acknowledges the support of the Canada Research Chairs program. For helpful discussions, the authors would like to thank Professors Eric Croiset and Keith W. Hipel, as well as Vahid Barahimi.

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Chapter 3

Applying equity principles leads to higher carbon removal obligations in Canada[1]

Abstract

Despite net-zero pledges, consensus on national responsibilities for carbon dioxide removal (CDR) strategies is lacking. Here, we use integrated assessment modeling to examine equity-informed estimates of Canada's remaining carbon budgets, exploring CDR's role at net-zero and beyond. Gigaton-scale CDR efforts post-2050 are needed to address Canada's carbon debt under various burden-sharing principles. Cumulative negative emissions (2050-2100) could increase from 7.5 $GtCO_2$ in the Net-Zero scenario to 20.3 $GtCO_2$ in equity-informed scenarios. By 2100, a CDR portfolio, including bioenergy with carbon capture and storage, direct air capture, and enhanced weathering could contribute up to ~500 $MtCO_2$/year of removals. The projected average CDR growth rates, 2.8%-16%/year, align with the historical adoption rates of ammonia synthesis and biomass consumption in Canada, underscoring the importance of drawing lessons from past successes. Socio-economic and technological sensitivity analysis highlights that, despite variations in the role of individual CDR technologies, CDR remains essential for Canada's post-net-zero commitments.

[1] This is an Accepted Manuscript of an article published by Nature Portfolio in *Nature Communications Earth and Environment* on 7 February 2025, available online: https://www.nature.com/articles/s43247-025-02080-z. K. Motlaghzadeh, N. Craik, J. Moreno-Cruz, V. Schweizer, J. Fuhrman, K. Hipel, "Applying equity principles leads to higher carbon removal obligations in Canada"

3.1 Introduction

The Paris Agreement sets a goal to limit global average temperatures to well below 2 degrees (ºC), while pursuing efforts to limit the temperature increase to 1.5ºC[1]. The remaining carbon budget (RCB), the permissible carbon dioxide (CO_2) emissions from a defined point in time that would limit global warming to agreed thresholds (e.g., 1.5°C), underscores the necessity of achieving and maintaining net-zero global CO_2 emissions as a cornerstone for meeting any climate target[2]. For two main purposes, carbon dioxide removal (CDR) methods are required to realize the 1.5ºC target. First, achieving net-zero emissions may require compensating for certain sectoral emissions that persist due to socio-economic or technological constraints, or a lack of mitigation strategies (e.g., in aviation). Second, exceeding the RCB results in a temperature overshoot that, in turn, necessitates CDR to reduce the concentration of CO_2 in the atmosphere to bring the temperature down to safe levels in subsequent years[3,4]. While overshooting the 1.5°C target may be considered ethically and strategically problematic, especially in light of irreversible climate change effects[5–7] and uncertainties regarding the long-term efficacy of CDR methods[8,9], recent RCB estimates, the level of ambition of climate policies, and current global CO_2 emissions suggest the overshoot of 1.5°C is highly probable[10].

The recognition that states will collectively exceed the RCB, leading to a form of carbon debt, has reignited calls for a transition to equity-driven national remaining carbon budgets (NRCB) in policy discussions[2]. Numerous studies have examined how to "fairly" share the RCBs associated with different temperature targets[11–13,13–18]. These studies draw on fairness principles that rely on different equity perspectives, such as the scale of countries' historical emissions and contribution to climate change (Responsibility), their ability to cut emissions and/or deploy CDR (Capability), equal emissions per-person (Equality) or mixed approaches[17].

Equity-based NRCBs, which would adjust a state's NRCB in light of fairness principles, provide a more ethically justifiable approach for states to determine the amount of CDR they may have to deliver to equitably contribute to achieving the Paris temperature goals. A broader set of implications flow from adopting equity-based NRCBs, particularly for states where the demands of fairness will increase the size of their carbon debt, resulting in increased responsibilities for CDR deployment. The policy choices concerning scaled-up CDR will influence other large-scale systems, such as energy and land use, and will increase infrastructure demands, such as geological storage. Integrated Assessment Models (IAMs) are essential tools for understanding the implications of interactions between socio-

technological and economic sectors, thanks to their capacity for modeling these complex dynamics. IAMs and scenario analysis can guide state strategies, especially for developing emerging CDR technologies and supporting physical, social and economic policies and regulatory frameworks.

This study focuses on Canada, recognized as one of the top ten countries worldwide in terms of per-capita emissions[19,20]. In 2022, Canada announced its Emissions Reduction Plan, outlining a framework of federal policies to reduce emissions to 40%-45% below 2005 levels by 2030 and set a long-term target of reaching net-zero greenhouse gas emissions by 2050. Current Canadian policy is silent on the demand for negative emissions to address drawdown beyond the 2050 net-zero goal. Previous Canadian studies have mainly focused on pathways compatible with the net-zero goal for 2050, through integrated modeling studies where their CDR portfolio was predominantly limited to bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC)[21–24]. While previous research has calculated NRCB for various countries, including Canada[17,25–27], there has yet to be a study exploring the implications of these estimates to net-zero targets and the role of CDR beyond net zero that equity principles may mandate for Canada.

We incorporate the concepts of burden-sharing and NRCB within a technologically comprehensive IAM framework guided by the equity principles of equal per capita (EPC-Q) and per capita convergence (PCC-Q), where "Q" denotes qualified approaches as defined and modified by Williges et al.[17]. Incorporating equity into an IAM framework allows us to examine the impact of different approaches to equity on Canada's NRCB and the role of various CDR technologies in reversing the temperature overshoot by the year 2100. Through the application of a tailored version of the Global Change Analysis Model (GCAM), as developed by Fuhrman et al.[39], we model various CDR strategies, including DAC, BECCS, enhanced weathering (EW), biochar, and direct ocean carbon capture and storage (DOCCS). This study examines the potential of CDR technologies and considers their energy requirements and the CO_2 storage needs these strategies may entail. In addition to our primary scenarios, we examine scenarios under different techno-economic uncertainties, such as the varying costs and accessibility of CDR technologies, the potential of land use (through afforestation and reforestation) to serve as a carbon sink and alternative futures with a strong socio-technological change towards renewable energy and low energy demand. Another crucial aspect this study examines is the growth rates of various CDR methods under modeled scenarios, comparing them to historically adopted technologies in Canada using a global dataset on technology adoption[28]. Finally, this study concludes by reflecting on the value of incorporating equity-based NRCBs into planning and policy discussions.

3.2 Results

We define our primary scenarios as follows: 1) No-Policy: A counterfactual baseline with no new climate policies and removal of all existing ones in Canada; 2) Net-Zero 2050: Canada achieves net-zero CO_2 emissions by 2050, maintaining this level thereafter; 3) EPC-Q 1.5°C Scenario: Canada reaches net-zero by 2050 and compensates for a carbon debt of 16.4 $GtCO_2$ based on the EPC-Q equity principle; and 4) PCC-Q 1.5°C Scenario: Canada attains net-zero by 2050 while addressing a carbon debt of 6.7 $GtCO_2$ following the PCC-Q equity principle. More information about different equity principles is available at Section 3.4.1. We explore emissions/removal pathways (Section 3.2.1), primary and final energy demand (Section 3.2.2), and potential geological CO_2 storage needs (Section 3.2.3). Sections 3.2.4 and 3.2.5 examine socio-economic and technological uncertainties affecting CDR deployment. Finally, section 3.2.6 compares modeled CDR growth rates with historical technology adoption and discusses associated challenges and barriers. Read more about the scenario design logic in Section 3.4.3 and Table 3-1.

3.2.1 Emission pathways and the role of carbon dioxide removal methods

As shown in Figure 3-1, In the No-Policy scenario, Canadian emissions remain largely unchanged, reflecting the continuation of existing practices. Conversely, in the Net-Zero scenario, we see a marked decrease in emissions across all sectors by 2050 compared to 2010, with reductions amounting to 64%, 76%, 90%, and 96% in transportation, industry, electricity, and buildings, respectively. To achieve a net-zero balance by 2050, the model incorporates various CDR methods, primarily focusing on BECCS for electricity production (60.3 $MtCO_2$), BECCS for hydrogen (H_2) production (33 $MtCO_2$), and a smaller scale of DAC at 3.7 $MtCO_2$. Post-2050, the use of CDR extends to non-biomass techniques. The maturity and wider availability of additional CDR methods will increase residual emissions from 115 to 195 $MtCO_2$ by 2100. In the Net-Zero scenario, by 2100, emissions from the transportation sector drop to 84 $MtCO_2$ per year—less than half of the 2022 levels (190 $MtCO_2$). However, these emissions still account for around 40% of the total positive residual emissions, making them notable. As shown in Supplementary Figure 1 in Appendix B, while road transportation—especially light-duty vehicles—undergoes substantial electrification, most of the remaining emissions come from hard-to-decarbonize sectors, such as heavy transport, large vehicles, trucks, and aviation. By the end of the century, DAC and EW contribute to removing approximately 63 and 12 $MtCO_2$, respectively.

Transitioning to the equity-based scenarios, illustrated in panels c and d of Figure 3-1, a notable surge in total negative emissions is observed post-net-zero, peaking at the end of the century. In 2100, DAC and EW are projected to remove approximately 308 and 70 $MtCO_2$ under the EPC-Q scenario, and 184 and 38 $MtCO_2$ under the PCC-Q scenario. Deployment of other CDR strategies, such as biochar and DOCCS, are anticipated to be minimal at their peak. Examination of the cumulative deployment of various CDR methods suggests that BECCS for electricity, BECCS for H_2, DAC, EW, biochar and DOCCS would be necessary within the ranges of 5700-6183, 1700-2318, 4000-8730, 598-1351, 107-110 and 0.01-0.02 $MtCO_2$, respectively, under different equity-based scenarios. Overall, cumulative negative emissions (2050-2100) increase by 12.8 $GtCO_2$, from 7.5 $GtCO_2$ in the Net-Zero scenario to 20.3 $GtCO_2$ in the ambitious EPC-Q 1.5°C scenario.

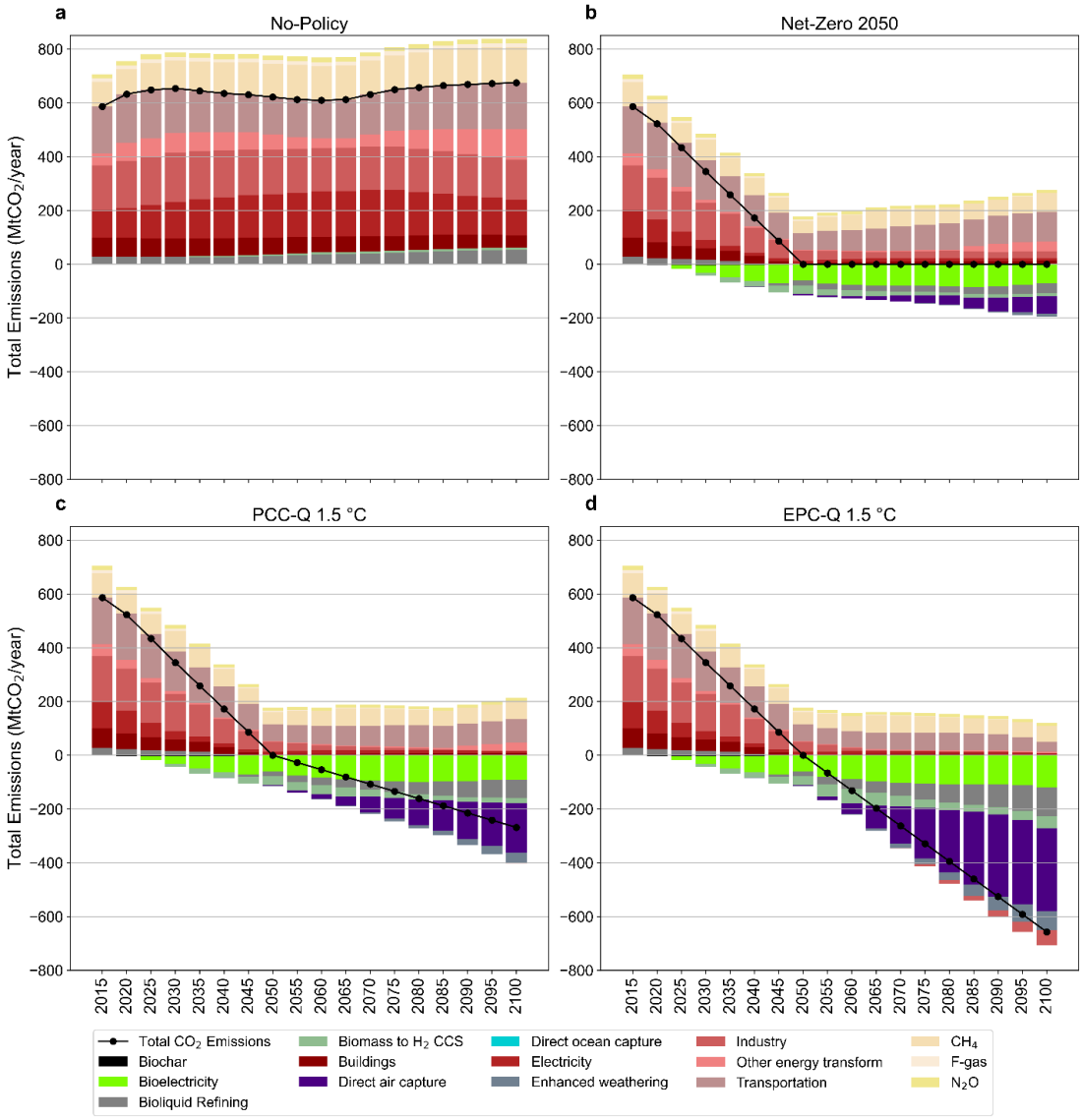

Figure 3-1. Emissions and removals by sector in Canada a, CO_2 and non-CO_2 emissions by sector in: **a**, the No-Policy counterfactual baseline scenario, which assumes no mitigation measures (e.g., carbon tax) are implemented. **b**, CO_2 and non-CO_2 emissions, along with CO_2 removal by sector, for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **c and d**, Sectoral emissions and removals under equity-based scenarios PCC-Q 1.5°C and EPC-Q 1.5°C, respectively (details provided in the Methods section). Different sectors are represented by distinct colors, and the black line indicates the total CO_2 emissions across all sectors.

3.2.2 Primary and final energy consumption pathways

Figure 3-2 illustrates the contributions to energy output of different technologies across different scenarios. In 2020, the primary energy sources were predominantly oil and gas, accounting for approximately 70% of total primary energy, followed by coal at 7.2%, biomass combustion (without CO_2 capture) at 5.8%, hydroelectric power at 11.5%, nuclear energy at 3.3%, and the remainder from solar, wind, and geothermal sources. Scenarios with climate policy introduce energy source variations. These include oil, gas, coal, and biomass combined with carbon capture and storage (CCS) technologies to neutralize their emissions. Specifically, in the Net-Zero 2050 scenario, there is a notable increase in the share of non-biomass renewable sources (reaching 30% of total primary energy by 2100), nuclear energy (12% by 2100), and biomass integrated with CCS (14% by 2100), coupled with a decrease in the contributions from coal, natural gas (without CCS), and biomass (without CCS). It is important to note that GCAM assumes CCS technologies will mature sufficiently later in the century to capture CO_2 at high rates. Supplementary Table 1 in Appendix B outlines the capture rates assumed for different technologies.

Similar trends are observed in the EPC-Q 1.5°C and PCC-Q 1.5°C scenarios, but the magnitude of change is more pronounced. For instance, in the EPC-Q 1.5°C scenario, by 2100, biomass with CCS comprises 25% of the total primary energy, and the proportion of fossil fuel use equipped with CCS is approximately 24-35% of the total fossil fuel consumption. As shown in Figure 3-2, despite the expansion of renewable energy production, fossil fuels (oil and gas) continue to play a substantial role, even by the end of the century. In the most ambitious EPC-Q 1.5°C scenario, fossil fuels still account for 26% of the energy mix. In Section 3.2.5, we present sensitivity analysis scenarios that explore alternative energy futures and their implications for CDR and emissions.

Figure 3-3 illustrates the types of final energy consumption under the scenarios discussed. In all scenarios, including the No-Policy one, the role of electricity in the final energy mix increases, indicating that electrification is likely to occur in nearly all scenarios. However, the rate of electrification is considerably higher in scenarios involving climate policies. By 2100, electricity constitutes 55-59% of the total final energy, compared to approximately 23% in 2020. As shown in Figure 3-3, refined liquids contribute noticeably to the final energy demand. A more detailed breakdown of the final energy demand supplied by refined liquids is provided in Supplementary Figure 2 of Appendix B, highlighting sectors such as transportation, construction, and other industries. To explore more ambitious deep decarbonization in these sectors, we conducted sensitivity analyses in

Section 3.2.5 of the paper. Figure 3-3 also details the proportion of final energy allocated to DAC, an energy-intensive CDR method. As previously discussed, in 2100, DAC is expected to remove 63, 184, and 308 $MtCO_2$/year in the "Net-Zero 2050", "PCC-Q 1.5°C", and "EPC-Q 1.5°C" scenarios. The model projects 2%, 6%, and 9% of electricity and 15%, 31%, and 41% of natural gas will provide the electricity and heat necessary for DAC.

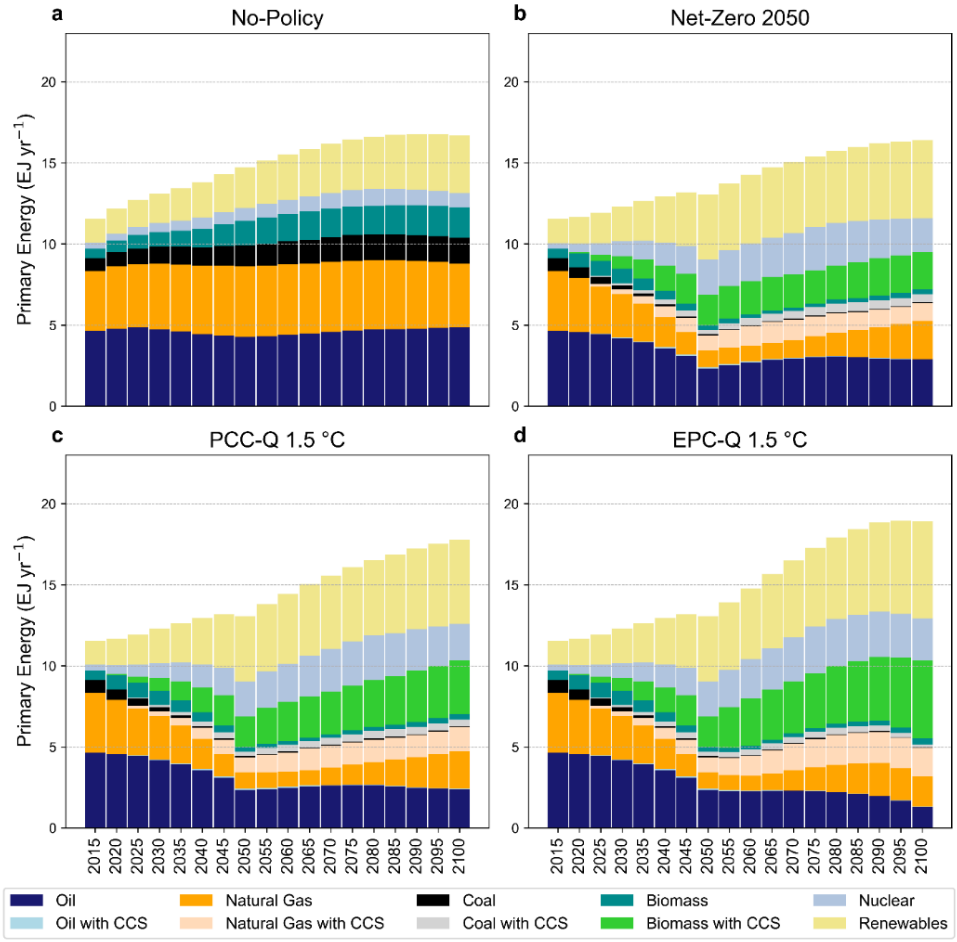

Figure 3-2. Primary energy production in Canada: a, Primary energy production by sector in: **a**, No-Policy counterfactual baseline scenario, which assumes no mitigation measures (e.g., carbon tax) are implemented. **b**, Primary energy production for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **c and d**, Primary energy production under equity-based scenarios PCC-Q 1.5°C and EPC-Q 1.5°C, respectively (details provided in the Methods section). Different energy technologies are depicted in distinct colors. For certain technologies, such as Oil, variants with carbon capture and storage (CCS) are included and labeled "with CCS.

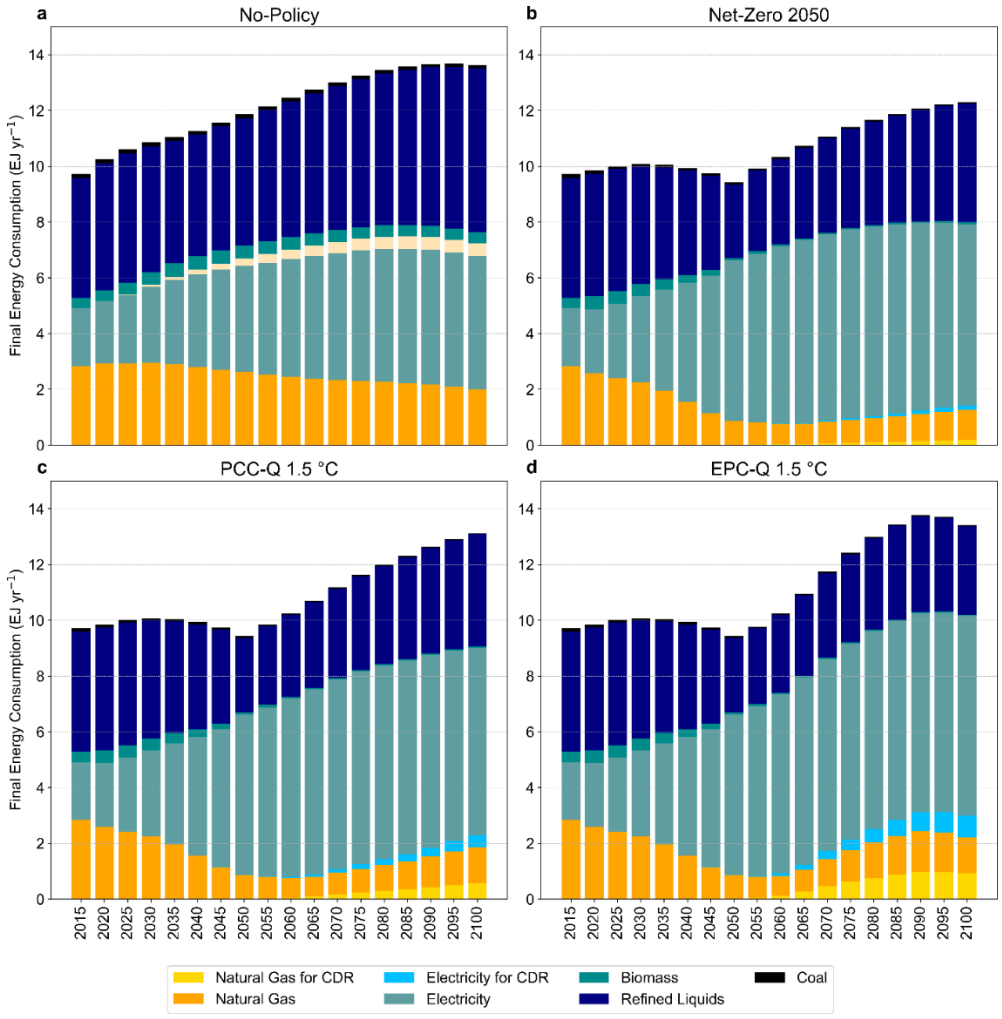

Figure 3-3. Final energy consumption by modes in Canada: a, Final energy consumption by mode in: **a,** No-Policy counterfactual baseline scenario, which assumes no mitigation measures (e.g., carbon tax) are implemented. **b,** Final energy consumption for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **c and d**, Final energy consumption under equity-based scenarios PCC-Q 1.5°C and EPC-Q 1.5°C, respectively (details provided in the Methods section). Different energy consumption modes are represented by distinct colors. The natural gas and electricity required for carbon dioxide removal methods are labeled "for CDR."

3.2.3 Potential need for geological storage

As illustrated in Figure 3-1 and Figure 3-2, numerous energy production pathways are integrated with CCS, alongside large deployments of CDR methods such as DAC and BECCS. The CO_2 captured by these diverse methods must be sequestered in stable mediums for extended periods. There are several options for CO_2 storage, but geological storage is the most promising because CO_2 can be securely contained for geological timescales. Geological storage is particularly viable in Canada due to the country's suitable geological characteristics and existing technical expertise derived from its oil and gas industry. Figure 3-4 outlines the annual rates of geological CO_2 storage required for Canada to meet its climate policy objectives through various implementations of DAC, BECCS, and CCS associated with fossil fuels and industry. By 2050, the model projects 315 $MtCO_2$ per year will need to be sequestered to meet the net-zero target, with this rate increasing to 853 $MtCO_2$ per year and 651 $MtCO_2$ per year by 2100 under the EPC-Q 1.5°C and PCC-Q 1.5°C scenarios, respectively. Canada is estimated to have the theoretical capacity for large-scale CO_2 storage, defined as the physical limit of CO_2 that the geological system can accept[29,30]. However, addressing social challenges, such as public acceptance, and overcoming regulatory barriers are critical prerequisites for realizing this potential[31]. The practical storage capacity, which accounts for geological, engineering, techno-economic, and socio-political constraints, represents only a fraction of the theoretical capacity[30]. Furthermore, since the locations of geological storage sites may not always align with potential CO_2 capture sites, scaling up CDR will necessitate major investment in CO_2 transportation infrastructure[32]. GCAM accounts for two main cost components in capture and storage technologies: capital and operating expenses, and region-specific CO_2 transport and storage costs based on updated supply curves from Dooley et al.[33].

3.2.4 CDR-related techno-economic uncertainties

Here, we explore how various sources of CDR-related uncertainties influence both the cumulative deployment throughout the century and the annual deployment in 2100, as illustrated in Figure 3-5. As shown in Table 3-1, our primary scenarios prohibit biomass imports to avoid shifting biomass production's negative externalities abroad, given Canada’s substantial biomass resources. For comparison, we include a scenario allowing imports. In these scenarios, the cumulative deployment of BECCS increases compared to the baseline, leading to reduced reliance on DAC and EW for both achieving net-zero emissions by 2050 (to offset residual emissions) and generating negative emissions thereafter. Specifically, cumulative DAC deployment declines from 1.5, 3.9, and 8.7 $GtCO_2$ in the

baseline scenarios (where biomass import is not permitted) to 1.1, 2.4, and 4.5 $GtCO_2$ under the Net-Zero, PCC-Q 1.5°C, and EPC-Q 1.5°C scenarios, respectively. Similarly, cumulative EW deployment decreases from 140–1350 $MtCO_2$ in the baseline scenarios to 62–822 $MtCO_2$ under scenarios with permitted biomass import. Since our primary scenarios rely heavily on BECCS, despite limited biomass imports, we explored how reduced biomass availability would affect the deployment of other CDR methods. In these scenarios, the cumulative deployment of DAC ranges from 3.8 to 9.6 $GtCO_2$, while EW increases from 400 to 1600 $MtCO_2$, depending on the scenarios. The yearly sectoral emissions/removals in these two scenarios are shown in Supplementary Figures 3 and 4 of Appendix B. In scenarios constrained by limited carbon storage capacity, the cumulative contribution of DAC is reduced by approximately 16% to 30%, varying with the equity principle applied. The yearly sectoral CO_2 emissions and removals in the limited carbon storage scenario are presented in Supplementary Figure 5 of Appendix B.

In limited DAC scenarios, where a cap was set on its yearly deployment—reaching 30 $MtCO_2$ by 2050 and 100 $MtCO_2$ by 2100 (more information on the scenario logic is available in Table 3-1)—we observe a reduction in the role of DAC (25–29%) and an increase in the roles of BECCS (7–15%) and EW (55–80%) for the equity-based scenarios. In scenarios with a low-cost trajectory for DAC, we observe a substantial increase in its cumulative deployment, with figures ranging from 5.5 (from 1.5) to 8.7 (from 6.4) $GtCO_2$, influenced by the chosen equity principle. By 2100, the annual deployment of DAC peaks at 261 and 344 $MtCO_2$ for the PCC-Q and EPC-Q 1.5°C scenarios, respectively. In contrast, a high-cost trajectory, assuming constant costs throughout the century, reduces DAC's cumulative deployment to just 2.2 $MtCO_2$ and 38 $MtCO_2$ for the Net-Zero and PCC-Q 1.5°C scenarios, respectively. However, in the EPC-Q 1.5°C scenario, our most ambitious pathway, DAC still plays a crucial role in achieving the necessary level of negative emissions, though its deployment decreases from 8.7 $GtCO_2$ in the primary scenario to 3.7 $GtCO_2$. This stark difference underscores DAC's sensitivity to cost and its competitive standing compared to other CDR strategies. The yearly sectoral emissions/removals in limited DAC, low-cost and high-cost DAC scenarios are shown in Supplementary Figures 6, 7 and 8 (Appendix B), respectively. In scenarios with limited EW availability, DAC's role increases slightly (up to 4% in equity-based scenarios) to offset the reduced contribution of EW. However, due to EW's overall smaller deployment compared to DAC, this increase is less significant. Yearly sectoral emissions/removals for the limited EW scenario are shown in Supplementary Figure 9 of Appendix B.

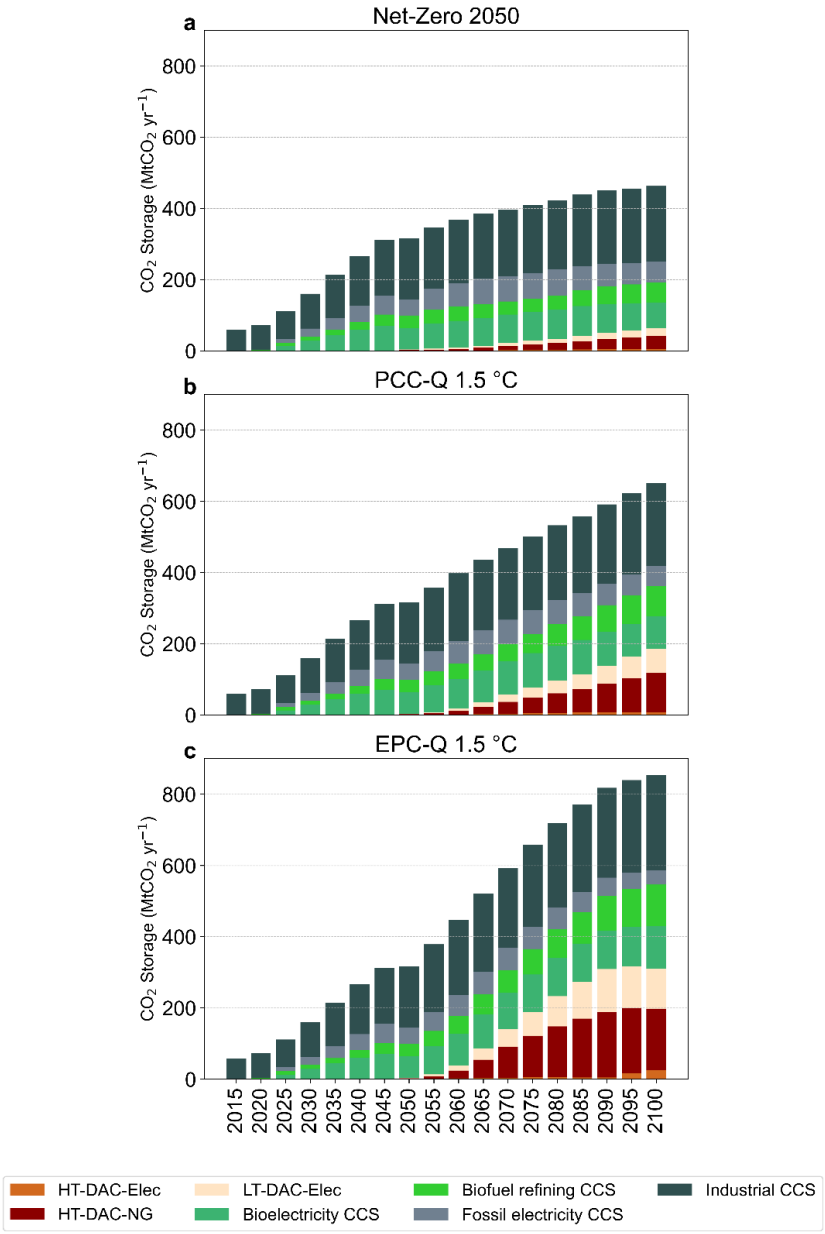

Figure 3-4. Required carbon storage in net-zero and equity-based scenarios in Canada: **a**, required carbon storage for a scenario where Canada achieves net-zero CO_2 emissions by 2050 and maintains it for the remainder of the century. **b and c**, Required carbon storage under equity-based scenarios PCC-Q 1.5°C and EPC-Q 1.5°C, respectively (details provided in the Methods section). Different CO_2 sources requiring storage are represented by distinct colors. For Direct Air Capture (DAC), the legend includes three technological variants: (1) high-temperature DAC with heat supplied by electricity (HT-DAC-Elec), (2) high-temperature DAC with heat supplied by natural gas (HT-DAC-NG), and (3) low-temperature DAC with heat supplied by electricity (LT-DAC-Elec).

In our primary scenarios, we do not account for emissions or removals from land use/cover within the emissions constraints. We prevent excessive dependence on carbon removal through traditional land management for several reasons: 1) The land-use sector in Canada alternates between acting as a carbon sink and a source of emissions; 2) There's an observed increase in wildfire occurrences, with 23% of total wildfire emissions in 2023 attributed to Canada[34]; 3) To prevent the model from heavily relying on land-use changes to achieve negative emissions—a strategy that GCAM often favors for its cost-effectiveness[35]. There are also a few factors that might inhibit a high level of carbon sink, such as 1) elevated management costs, some of which are coming from monitoring, validation, and regulation of the land carbon sequestration projects to ensure additionality[36], 2) The risk of reversal, where carbon is released back into the atmosphere either intentionally through land-use decisions or unintentionally due to climate-related extremes such as storms and wildfires[37]. Although these challenges led us to exclude land-based carbon removal from our primary scenarios, in this section, we explore the implications of effectively addressing them. We assume Canada implements a successful land-management strategy capable of removing 50 $MtCO_2$ by 2050, a figure consistent with current literature and the recent Energy Future Report[22]. This is particularly important given that in IPCC scenarios, land-based carbon removal (through afforestation and reforestation) methods play a crucial role in the near term, while novel CDR methods are projected to have a marked impact later in the century, helping to balance residual emissions and reverse temperature overshoot[38].

For the ambitious EPC-Q and PCC-Q 1.5°C scenarios, we anticipate an increase in land removals to 100 $MtCO_2$ by 2100. In scenarios where land use acts as a carbon sink, there's an observable increase in residual positive emissions for 2050—approximately 14% higher than in baseline scenarios. A closer examination of cumulative negative emissions reveals the pivotal role of land-use carbon removal, contributing 3.4-4.7 $GtCO_2$ across various scenarios. This also corresponds with a decrease in the cumulative deployment of other CDR methods, including a 12-28% reduction for DAC, 18-65% for EW, 12-14% for BECCS for electricity, and 17-23% for hydrogen production from biomass. The yearly sectoral emissions/removals in a scenario with land-based CDR are shown in Supplementary Figure 10 of Appendix B.

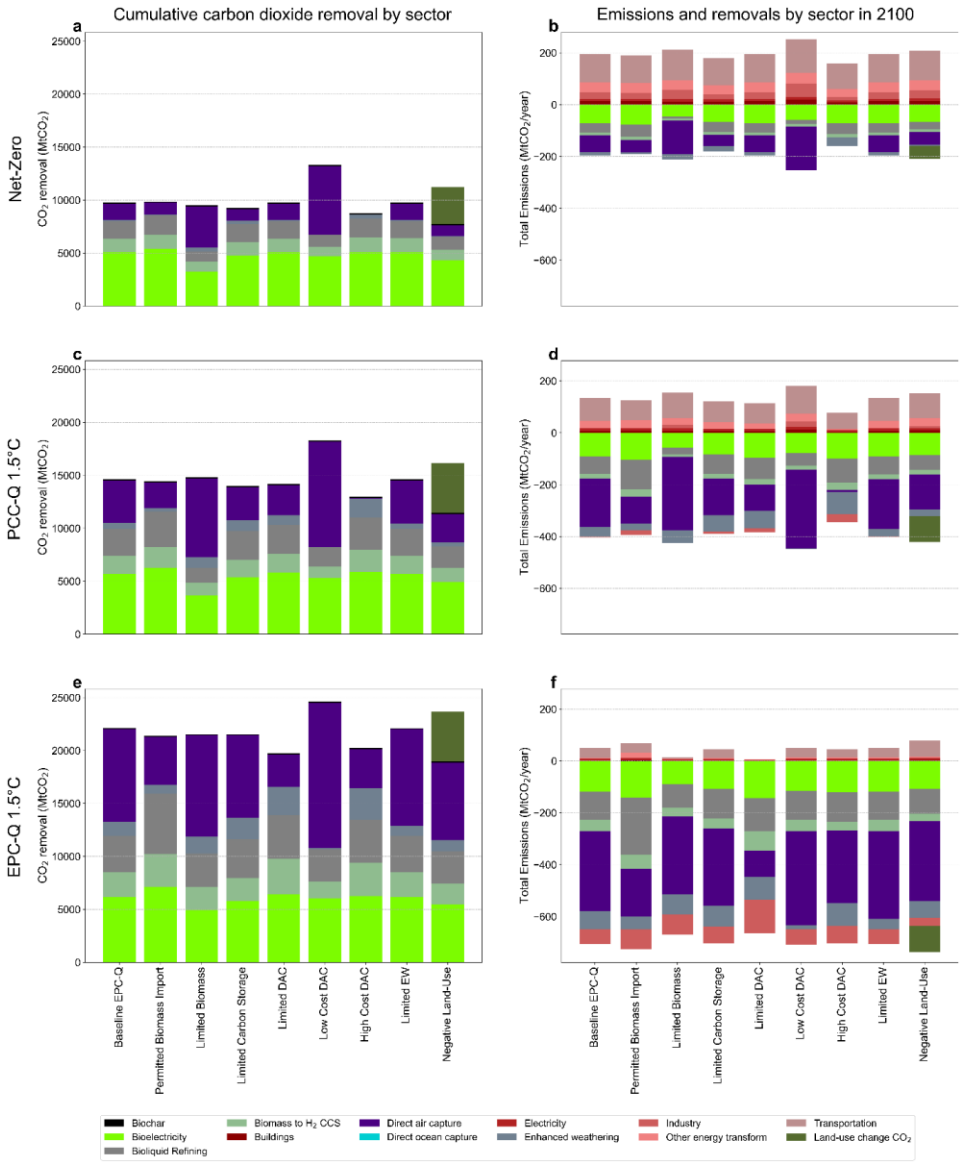

Figure 3-5. CO_2 Emissions and removals under different techno-economic uncertainties in Canada. **a, c, and e**, Cumulative CO_2 removal by different technologies across sensitivity analysis scenarios (detailed on the X-axis, with further information in Table 3-1) for the net-zero (a), PCC-Q 1.5°C (c), and EPC-Q 1.5°C (e) scenarios. **b, d, and f**, CO_2 emissions and removals in 2100 by different technologies across sensitivity analysis scenarios for the net-zero (b), PCC-Q 1.5°C (d), and EPC-Q 1.5°C (f) scenarios. Different sources of emissions and removals are represented using distinct colors.

3.2.5 Future energy pathway and DAC variants availability

This section explores how an alternative future with considerable socio-technological change (STC) impacts energy use, emissions, and CDR deployment. The STC scenario, based on the SSP1 "Sustainable Development" storyline, emphasizes renewable energy, reduced biomass reliance, improved efficiency, lower energy demand, deep transportation decarbonization[39,40], and limited nuclear growth. A variant, "STC with No HT-DAC-NG," excludes natural gas-powered DAC to further reduce fossil fuel reliance. We compare these scenarios' energy characteristics, emission pathways, and CDR deployment with our primary scenarios.

As shown in Figure 3-6a, nuclear energy in STC scenarios drops significantly to 1–2% by 2100, compared to 12% in baseline scenarios. Fossil fuel energy production declines to 13% in the EPC-Q 1.5°C STC scenario (26% in the baseline scenario) and further to 9% when HT-DAC-NG is excluded. Final energy demand (shown in Figure 3-6b) also decreases markedly, with electrification rising to 62–77% and natural gas reliance falling to 2–10%. In the EPC-Q 1.5°C scenario, DAC electricity use increases from 5.8% to 8.4% under STC, reaching 10.4% when HT-DAC-NG is excluded. Meanwhile, natural gas use for DAC drops from 6.8% to 3.7% and to zero when HT-DAC-NG is unavailable, underscoring a clear shift away from fossil fuels in STC scenarios.

The reduction in final energy demand, combined with Canada's cleaner energy mix in the STC and STC without HT-DAC-NG scenarios, significantly lowers residual emissions by 2100, reducing reliance on CDR. As shown in Figure 3-7b, STC scenarios have shorter bars above the year axis compared to the baseline, reflecting lower residual emissions. For example, residual CO_2 drops from 195 $MtCO_2$ in the baseline Net-Zero scenario to 94 $MtCO_2$ in 2100. In the most ambitious scenario, EPC-Q 1.5°C, emissions decrease further from 50 to 7.5 $MtCO_2$ in the "STC and No HT-DAC-NG scenario." This substantial reduction is largely driven by the transportation sector, which sees lower emissions due to reduced demand and stronger decarbonization efforts. Detailed comparisons are provided in Section B1 and Supplementary Figures 1, 2, and 11 of Appendix B.

In our scenarios, CDR plays two primary roles: (1) compensating for residual emissions and (2) achieving negative emissions to meet equity-driven targets. In the STC scenarios, the need for CDR to address the first goal is dramatically reduced due to stringent emissions reductions and minimized residual emissions. However, as shown in Figure 3-7a, in our equity-focused scenarios, EPC-Q and PCC-Q 1.5°C, CDR still play a pivotal role. Various methods such as BECCS for electricity (4.2 to 5.9

$GtCO_2$), BECCS for hydrogen (1.3 to 2.5 $GtCO_2$), DAC (4.1 to 7.3 $GtCO_2$), and enhanced weathering (1.8 to 2.6 $GtCO_2$) remain crucial, despite a slight decrease due to the reduction in residual emissions.

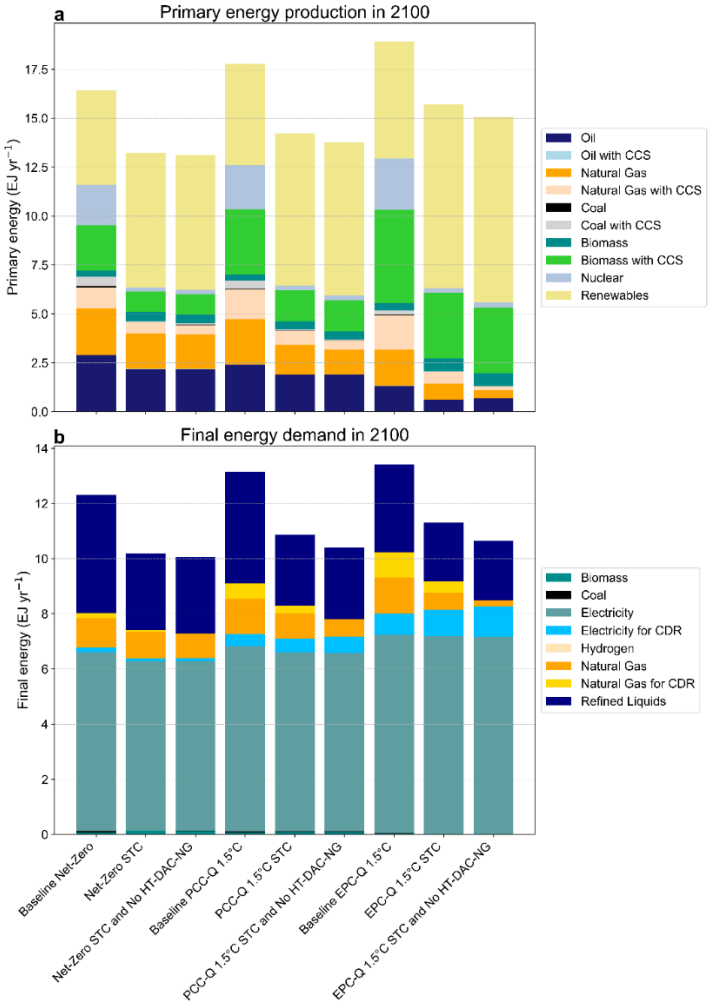

Figure 3-6. Future energy characteristics under alternative socio-technological pathways in Canada. **a**: Primary energy production in 2100 by different sources under baseline and alternative socio-technological scenarios. **b**: Final energy consumption by mode in 2100 under baseline and alternative socio-technological scenarios. Baseline scenarios are labeled with "baseline" at the beginning of the name, while alternative socio-technological pathways are labeled with "STC" (socio-technological change) and "STC and No HT-DAC-NG," which excludes high-temperature DAC technology that its heat is supplied by natural gas from the model's technology portfolio. Further details on scenario logic can be found in Table 3-1.

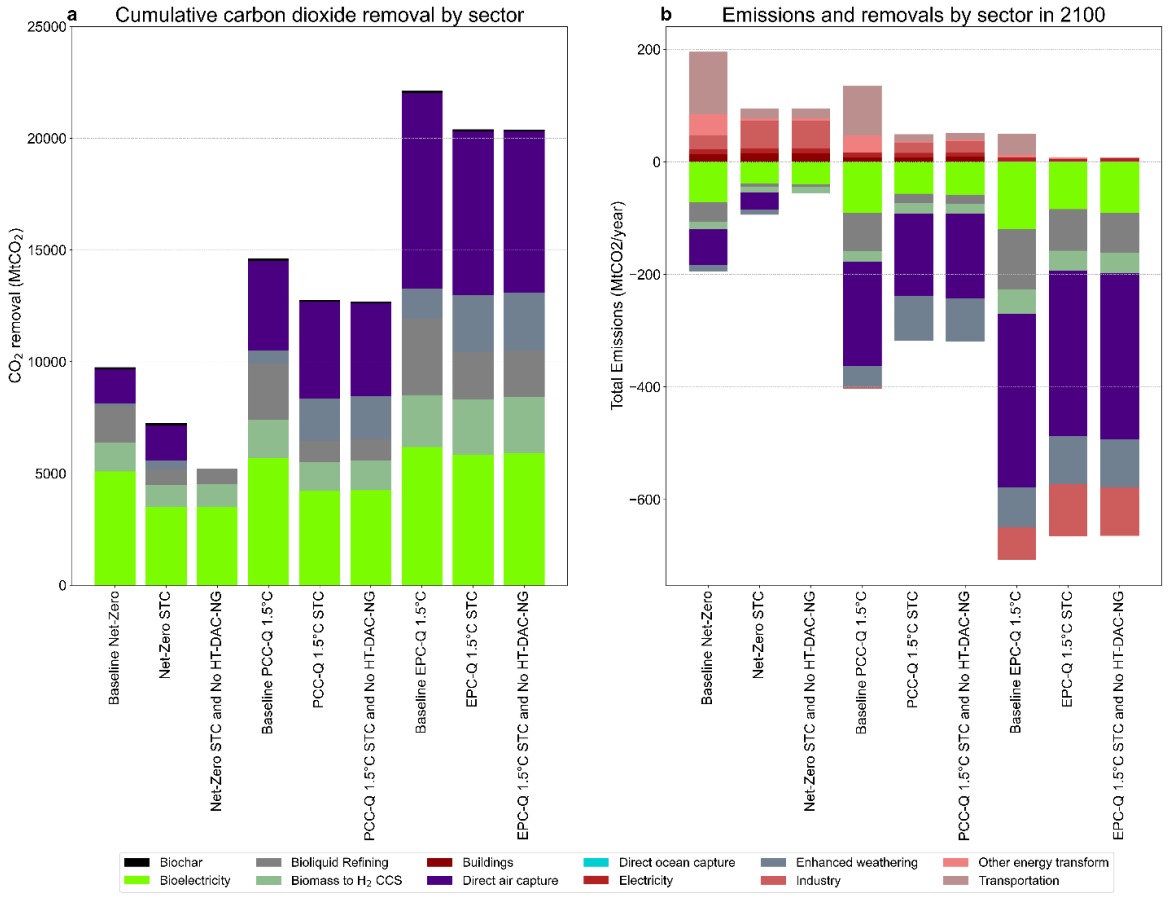

Figure 3-7. CO_2 Emissions and removals under alternative socio-technological pathways in Canada. **a:** Cumulative CO_2 removal by different technologies under baseline and alternative socio-technological scenarios. **b:** CO_2 emissions and removals in 2100 by different technologies across alternative socio-technological scenarios. Baseline scenarios are labeled with "baseline" at the beginning of the name, while alternative socio-technological pathways are labeled with "STC" (socio-technological change) and "STC and No HT-DAC-NG," which excludes high-temperature DAC technology that its heat is supplied by natural gas from the model's technology portfolio. Further details on scenario logic can be found in Table 3-1.

3.2.6 Growth rates of CDR vs. historical technology adoption in Canada: uncertainties and challenges

CDR technologies are crucial for meeting policy targets, especially by century's end in EPC-Q and PCC-Q scenarios. Currently, non-land-based methods like DAC are in their early stages, with minimal deployment, high risks, and limited resources. Nemet et al.[41] examined global scenarios aligning with Paris Agreement temperature goals, concluding that novel CDR technologies must be developed within

the next 15 years to move past the formative stage and achieve dramatic scaling post-formation. The formative phase is crucial in determining the trajectory of a technology during its subsequent expansion; however, overcoming barriers during the scale-up phase is equally critical. Based on the literature on the early stages of technology development[28,42], the formative phase is considered complete when technology reaches 2.5% of its eventual saturation.

In this section, we are interested in comparing the growth rate in CDR technologies as projected by our model to historical rates. To do this, we calculated both the average and maximum growth rates of various CDR technologies from the end of the formative phase to full saturation. These rates were compared with the historical average and maximum growth rates of 20 pathways associated with the adoption of energy and chemical materials in Canada, as recorded in the Historical Adoption of TeCHnologies (HATCH) dataset[28,43]. These technologies were classified into two categories: 1) energy (e.g., nuclear power) and 2) chemicals and material productions (e.g., ammonia synthesis), with a comprehensive classification presented in Supplementary Table 2 of Appendix B.

Figure 3-8 illustrates the comparative analysis of the average and maximum growth rates for technology adoptions across different scenarios. The growth rates are detailed for different CDR methods including BECCS for electricity and hydrogen production, EW, and three variants of DAC. In our primary scenarios, BECCS for electricity and H_2 production exhibit average growth rates of 2.8-3.8% and 11.6-16.1% per year, with maximum growth rates of 18% and 68% per year, respectively. EW demonstrates an average growth rate of 7.6-9.6% per year and a maximum of 22-27% per year between 2058 and 2086, varying by scenario. DAC technology variants typically require an average growth rate of 7 -8.1% per year from the end of their formative phase until they achieve maximum capacity by 2100. The peak growth rate for DAC occurs between 2048 and 2060, depending on the technology variant and specific scenario. In scenarios where DAC deploys at a greater scale—either due to limited biomass supply or relatively lower costs—the average and maximum growth rates can escalate to as high as 9.7% per year and 44% per year, respectively.

When comparing these rates to historically adopted technologies in Canada after their formative phases, the projected growth rates for CDR technologies are notable yet not unprecedented. For instance, the production of biofuels in Canada, post its formative phase in 1999, maintained an average growth rate of 23.2% per year, peaking in the 2006-2007 period with a nearly threefold increase (191%). Similarly, ammonia synthesis, after its formative phase in 1961, experienced an average growth rate of

7.8%, with a peak of 55% in 1975-1976, reaching its zenith in 1999. A key point about this example is that the literature highlights ammonia synthesis, an energy-intensive chemical technology for processing atmospheric gases, as an analogous technology to high-temperature DAC. Both ammonia synthesis and DAC are processes characterized by their high energy intensity. Historically, ammonia synthesis was expanded during the world wars and the Green Revolution, demonstrating how industrial technologies can be scaled up in response to global needs. Similarly, DAC could be expanded as an emergency response to the climate crisis[44]. Furthermore, ammonia synthesis intervenes in the nitrogen cycle by industrially converting nitrogen to ammonia, while DAC intervenes in the carbon cycle by capturing atmospheric carbon dioxide[41,45]. The Canadian DAC growth rate projection (7 -8.1%) is very close to how Canada has historically expanded ammonia synthesis.

Although reducing emissions and approaching net zero is the primary and most critical step, Canada's carbon debt can only be addressed through CDR, whether by domestic deployment or future participation in international CDR markets. While Figure 3-8 shows that the growth rates projected for BECCS, EW, and DAC are comparable to those achieved by other technologies in Canada, scaling up these methods presents critical challenges.

For example, the most pressing problem for scaling up BECCS is the rising demand for land, water, and fertilizers, which can directly compete with food production and put pressure on already limited world resources. When expanded to fulfill climate targets, the land and water footprint of BECCS may have a detrimental impact on environmental goals like ecosystem services and biodiversity protection. Logistical problems further hinder BECCS implementation. Large-scale biomass agriculture raises the need for agricultural water and nitrogen fertilizers, both of which are resource-intensive and can cause environmental deterioration[46]. Although technical solutions such as employing agricultural leftovers or algal biomass can alleviate part of the land-use demand, these approaches still challenge scalability and resource availability limitations[47].

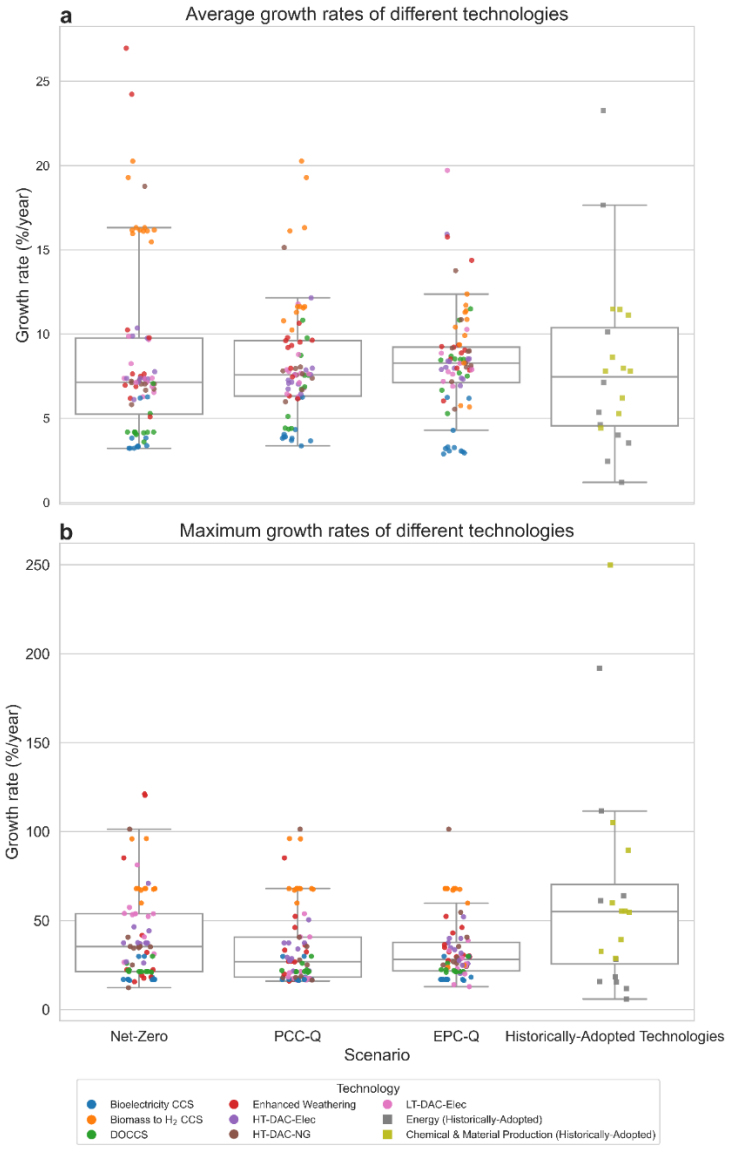

Figure 3-8. Comparative analysis of growth rates for carbon dioxide removal technologies and historically adopted technologies in Canada: **a,** Average yearly growth rate (%/year) of various carbon dioxide removal (CDR) technologies under the Net-Zero and equity-based scenario families, including EPC-Q 1.5°C and PCC-Q 1.5°C, across all primary and sensitivity scenarios listed in Table 1. The plot also includes two categories of historically adopted technologies[43] in Canada, grouped under 'Historically Adopted Technologies.' These technologies are classified into 1) Energy and 2) Chemical & Material Production. **b,** Maximum yearly growth rate (%/year) for the same scenarios and technologies. Classification of historically adopted technologies is provided in Supplementary Table 2 of Appendix B.

Similarly, with EW, a major worry is the possible release of harmful components from industrial wastes used in EW, which might pollute soil and endanger food safety[48]. Furthermore, the energy required for mining, crushing, and transporting rock powder may jeopardize the process's long-term viability if it is not fueled by renewable energy[49].

DAC is frequently regarded as a more flexible CDR option due to its lower land-use requirements when compared to other methods. However, its high energy intensity poses a challenge. DAC systems use a lot of energy, and unless they're powered by low-carbon energy sources, their overall carbon removal potential may be limited[50,51]. In addition to energy demands, DAC technologies have large material requirements. While the input requirements for chemical sorbents do not limit the scalability of DAC, material efficiency improvements are required to reduce environmental impacts and optimize resource use, as well as to ensure the technology's viability and social acceptability[51]. The economic feasibility of DAC presents an evident challenge, with costs varying from $30 to $600 per tonne of CO_2 captured, rendering it economically impractical without substantial policy intervention, including carbon pricing or subsidies[52]. Concerns exist regarding the potential burden on local infrastructure, especially in economically disadvantaged communities. In California, for instance, there are fears that DAC facilities could lead to increased energy costs for ratepayers, especially in low-income areas already burdened by other waste-processing infrastructure[53]. Additionally, logistical challenges related to CO_2 transport and storage, along with the need for extensive renewable energy infrastructure, further complicate the large-scale deployment of DAC.

3.3 Discussion

In this study, we explored the potential roles of various CDR methods at the point of achieving net-zero and the potential evolution of their roles beyond the net-zero year under two burden-sharing frameworks, which are EPC-Q and PCC-Q, incorporating historical emissions, benefits derived from those emissions, and countries' capabilities to undertake mitigation actions[41]. We also examined how the role of CDR might shift under principles that disregard these equity dimensions, as discussed in Section B2 and illustrated in Supplementary Figure 12 of Appendix B.

In addition to the quantitative results of CDR methods deployment, we offer insights into the different dimensions related to national and global equity, CDR and decision-making. The discussion of equity in the context of the Paris Agreement is not just a policy preference but an international legal commitment, as outlined in Article 2[1]. Beginning to apply a quantitative framework to the varying

definitions of equity in modeling exercises can help inform actionable CDR policies for decision-makers. This study provides deeper insights into the scale of CDR required at the national level to meet fairness commitments, specifically for Canada.

Implementing equity is not just about doing more in terms of reductions and removals; different approaches to equity lead to drastically different national-level mitigation portfolios. This is evident in the increased requirements for EW and DAC in the EPC-Q 1.5°C scenario and the varying energy, land use, and geological storage needs associated with scaled-up levels of CDR. Understanding the broader system requirements of equity-driven climate policy is crucial for long-term planning decisions within national polities. Equity-consistent decisions must be made in the medium term (next 10 to 15 years). The study suggests several low-regret policy choices that are necessary across various scenarios, such as increased use of land-based carbon sinks, development of geological storage infrastructure, and a diversified energy supply. The study also highlights the tension between global and local equity demands. The equity-based approaches modeled reflect global considerations of fairness in burden distribution among states. However, local inequities may arise at the national level, particularly in land-use decisions driven by technologies such as BECCS, which may impose localized burdens. Similarly, fixed geological storage opportunities can lead to localized burdens. Substantial national-level investment is needed for global equity, but this may revive earlier debates on burden-sharing that were set aside with the Paris Agreement framework.

Finally, the study identifies potential constraints on realizing equitable outcomes. Technology adoption rates are one such constraint, and comparing the needed rates with other historically adopted technologies in Canada reveals the potential feasibility of CDR deployment at scale. Conditions enabling rapid technological scaling and their applicability to CDR require deeper investigation. Our models assumed that Canada would implement all CDR methods domestically. However, the development of an integrated international CDR market may prompt countries to invest in CDR deployment abroad, particularly when facing feasibility challenges domestically[13,54]. Differences between NRCB-based and global modeling may highlight cost-effective opportunities outside Canada that can be pursued through technology transfer and international trading, in alignment with equity principles.

Moving forward, there are areas where future studies could build upon our work. One recommendation is to incorporate non-CO_2 greenhouse gas emissions more explicitly. In this study,

NRCBs were calculated based solely on CO_2 budgets, as carbon removal methods are primarily focused on CO_2 emissions. However, between 2050 and 2100, non-CO_2 emissions are projected to range from 60 to 80 $MtCO_2$-equivalent (Figure 3-1), which suggests that CDR methods might play an additional role in offsetting these emissions if no specific policies are enacted to reduce them. It is important to note that nearly all our scenarios depend on substantial decarbonization across various sectors, partly facilitated by CCS technologies. GCAM assumes these technologies will reach high capture rates once they are fully mature. However, current real-world capture rates may be considerably lower than GCAM's assumptions[55], underscoring the need for a more detailed sensitivity analysis of varying capture rates.

3.4 Methods

3.4.1 Equity-based national remaining carbon budget (NRCB)

The allocation of NRCBs will be determined by the definition of fairness used[56] and other modeling assumptions[57]. This allocation, in turn, determines how the transition costs and burdens of climate policy are distributed across countries. There have been multiple studies in the burden-sharing literature that address sharing the remaining carbon budget[17,25,27,58,59] or global CDR deployments[11,13,14] that are required for meeting climate targets. Two of the burden-sharing approaches for conducting such analysis include equal per capita (EPC) and per capita convergence (PCC). EPC and PCC methods offer contrasting strategies for distributing the remaining carbon budget, rooted in different justice philosophies[17]. EPC promotes an egalitarian principle by allocating equal emission rights to every individual from the present until a set future date, such as 2050. This approach underscores an equitable distribution from the outset, disregarding the existing disparities in emissions among nations. Conversely, PCC acknowledges these current disparities by starting with the unequal levels of emissions and population shares, and it aims for a gradual shift towards equal per capita emissions by the end of the budget period. This transition reflects a more pragmatic approach, allowing for a phased reduction in emissions, particularly benefiting wealthier, higher-emitting countries during the initial phase. While PCC seeks to address the practical challenges of global emission reduction by accommodating existing inequalities, it faces criticism for initially favoring nations that have historically emitted more[17]. In particular, PCC incorporates a form of grandfathering, which Rajamani et al.[56] have indicated is not supported by international legal principles. However, PCC does reflect the

incremental approach to mitigation ambition seen in many developed states' Nationally Determined Contributions.

Williges et al.[17] amended the EPC and PCC models to better align with fairness principles in three ways:

1) N-qualified: Implementing a basic needs threshold using the Human Development Index to determine initial CO_2 allocations, ensuring that countries below this threshold are supported to meet basic living standards before a standard emission distribution is applied.
2) H-qualified: Adjusting the historical accounting start date to 1995, recognizing countries' awareness of climate impacts by then and incorporating this into their emission responsibilities.
3) B-qualified: Accounting for the benefits derived from emissions prior to 1995, deducting these from the emission shares of benefiting countries, to reflect the long-term effects of their past activities.

In applying equity principles to Canada's NRCB, we adopt these approaches (as opposed to, for example, ones based solely on historical emissions) with all three modifications (EPC NHB-qualified and PCC NHB-qualified) since these provide, in our view, a compelling and multi-dimensional approach to equity. Both equity principles take into account the basic needs of countries, historical emissions (from 1995), and benefits derived from past emissions[17]. In Figure 3-9, we show different estimates of NRCB starting 2017 based on EPC NHB-qualified and PCC NHB-qualified for the 1.5 °C target. For this paper, we will refer to EPC NHB-qualified and PCC NHB-qualified as EPC-Q and PCC-Q, respectively, where "Q" stands for "Qualified." In Section B2 (in Appendix B), we also examine EPC Simple and PCC Simple to assess the potential implications of these approaches for Canada's post-net-zero carbon removal strategies. However, since EPC Simple and PCC Simple do not consider historical emissions, the basic needs of nations, or the advantages certain countries have gained from their past emissions, they are misaligned with several key equity principles. Further details on the equations and methodology used to quantify these principles can be found in Williges et al.[17].

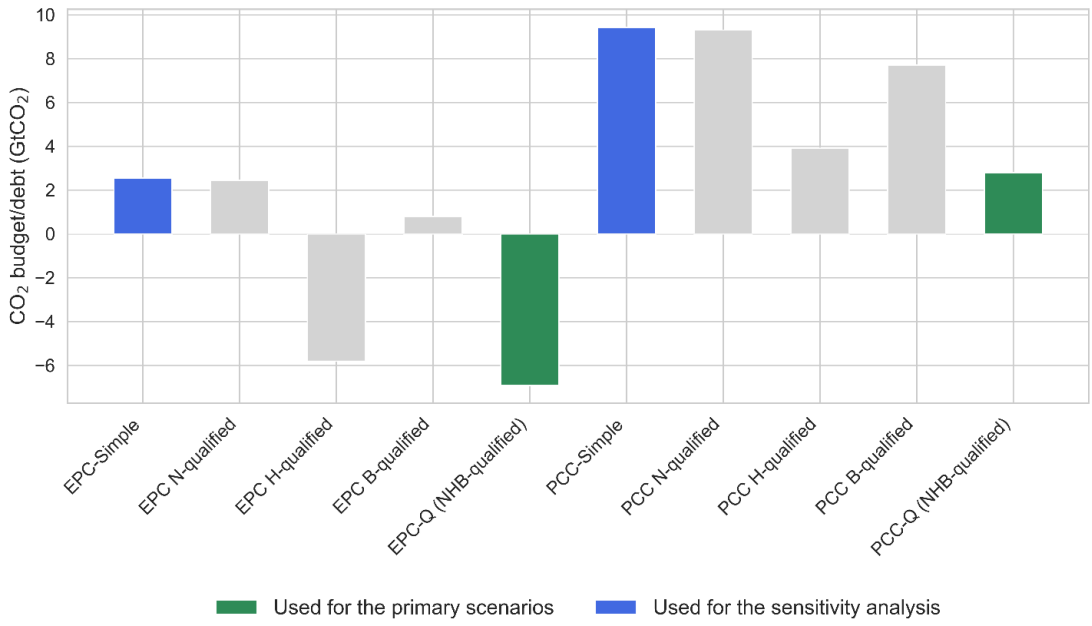

Figure 3-9. Remaining carbon budgets for Canada under different equity principles.

3.4.2 GCAM and CDR representation

GCAM is a comprehensive integrated assessment tool that simulates interactions between energy, water, land, economy, and climate systems across 32 global regions. It finds the market equilibriums from 1990 to 2100 with updates every five years. By integrating these systems within its core rather than treating them as separate modules, GCAM provides insights into macroeconomic trends, energy supply and demand, agriculture and land use changes, and water usage, underpinned by population and productivity projections[60]. Since the primary objective of this study is to investigate the role of CDR methods in achieving net-zero and post-net-zero scenarios, we have chosen to utilize a specific version of the GCAM 5.4, as developed by Fuhrman et al.[39]. This version was selected for its enhanced capability to integrate various CDR approaches:

- Direct air capture (DAC): DAC involves several technologies aimed at extracting dilute CO_2 directly from the atmosphere[61]. In GCAM, DAC includes high-temperature solvent-based processes (HT-DAC), powered by either electricity or natural gas, and low-temperature (LT-DAC) options powered by electricity, each evolving in efficiency and cost [62].
- Direct ocean carbon capture and storage (DOCCS): DOCCS utilizes the ocean's higher CO_2 concentration, over 120 times that of the atmosphere, to capture CO_2 through electrochemical

processes. This captured CO_2 is then geologically stored, allowing the ocean to absorb more atmospheric CO_2. In GCAM, this is modeled through stand-alone and integrated desalination technologies[39].

- Bioenergy with carbon capture and storage (BECCS): BECCS combines bioenergy production from biomass with CO_2 capture and storage, aiming for negative emissions by balancing the CO_2 absorbed by biomass growth with that released during energy conversion[61]. GCAM models BECCS across multiple sectors to assess its impact on land, water, and emissions[39].
- Enhanced weathering (EW): EW accelerates natural weathering processes to increase CO_2 sequestration by treating rocks to increase their reactive surface area. This method is aimed at transforming weathering from a geological to a human timescale[61]. In GCAM, EW is represented by the application of crushed basalt on lands, with considerations for cost, land use, and environmental impacts[39].
- Biochar: Biochar is produced through the pyrolysis of organic materials in an oxygen-limited environment, resulting in a stable form of carbon that can enhance soil properties when applied to land[61]. In GCAM, biochar is modeled as a soil amendment that competes with the direct use of biomass feedstock for energy (i.e., BECCS) impacting soil carbon stocks. It can also possibly improve agricultural crop yields[39].

3.4.3 Scenarios and their socio-technical assumptions

We integrated Canada's commitment to reducing greenhouse gas emissions by 40-45% by 2030, aiming for net-zero emissions by 2050[63] as constraints within our GCAM model. Since the primary focus of this study is on the implications of the burden-sharing mechanism on the national deployment of CDR methods, and the remaining carbon budgets are calculated specifically for CO_2, we make a simplifying assumption that the government's targets apply exclusively to CO_2 emissions rather than all greenhouse gases. The model iteratively seeks market equilibrium across various Canadian sectors, ensuring alignment with the specified emission reductions. We then calculate cumulative emissions from 2017 to 2050. By comparing these cumulative emissions to the NRCBs starting from 2017 (as shown in Figure 3-9), we assess Canada's carbon budget or deficit by 2050. This assessment is conducted under both the EPC-Q and PCC-Q equity principles, in the context of limiting warming to 1.5°C targets. This assessment informs the emission constraints for every subsequent five-year period up to 2100, to utilize any remaining budget or address any carbon debt.

Canada faces a carbon debt (see the results section) under all assessed equity principles and temperature targets, indicating the necessity for net-negative emissions post-2050. Using GCAM, we project how these negative emissions could be realized through various CDR methods in the years following 2050. From the net-zero year through to 2100, a linear ramp-up of negative emissions reaches a peak in 2100. A detailed example of such a calculation is available in Section B3 along with Supplementary Figures 13 and 14 (in Appendix B). In our analysis, we conducted several scenarios to explore various sources of socio-technical uncertainties. Table 3-1 outlines these scenarios and provides their descriptions. To streamline the presentation of our results, we categorized these scenarios into two groups: primary scenarios, which are discussed thoroughly in the results section, and others, which are examined in the context of sensitivity analysis. Given that the primary scenarios are subject to numerous sources of uncertainty, sensitivity analysis is employed to provide further insights into the impact of key variables. These latter scenarios differ in terms of the inclusion of removals from the land-use sector, temperature targets, and the techno-economic assumptions and constraints associated with different CDR methods, thereby offering a comprehensive understanding of potential outcomes.

Table 3-1. Defining scenarios, their underlying logic and techno-economic assumptions

Scenario	Type	Burden-sharing principle	Scenario design elements and logic
No Policy	Primary	Not applicable.	The "No Policy" baseline scenario assumes the absence of climate policies and aligns with the "middle-of-the-road" shared socio-economic pathway or SSP2[64]. In this scenario, all of Canada's climate and mitigation measures, including carbon pricing, are eliminated. Although this scenario is less likely given recent investments, it is included to reflect the considerable political uncertainty surrounding Canada's climate objectives. For example, Canada was the first country to withdraw from the Kyoto Protocol[65,66].
Net-Zero 2050			In this scenario, Canada meets its 2030 emissions target of 344 $MtCO_2$, reflecting a 40% reduction from the 2005 level of 575 $MtCO_2$. After 2030, emissions are reduced linearly to achieve net zero by 2050.
EPC-Q 1.5 ˚C		EPC NHB-qualified	After achieving the 2030 emissions reduction target and the 2050 net-zero goal, Canada is projected to incur a carbon debt of 16.4 $GtCO_2$ (Section B3 of Appendix B provides the calculation steps), based on the EPC-Q burden-sharing principle. To address this debt, Canada will ramp up its negative emissions efforts, reaching a peak in 2100.
PCC-Q 1.5 ˚C		PCC NHB-qualified	Similar to the EPC-Q 1.5 ˚C scenario, but with the carbon debt calculated using the PCC-Q burden-sharing principle, it resulted in 6.7 $GtCO_2$ (calculation steps are provided in Section B3 of Appendix B).
Permitted biomass Import	Sensitivity analysis	Three variants with respect to Net-Zero 2050, EPC-Q 1.5˚C and PCC-Q 1.5˚C	In all of the primary scenarios, it is assumed that Canada cannot import biomass, to prevent shifting the negative externalities of logging activities to other countries [67]. This is particularly important given that Canada has abundant domestic biomass resources and acknowledges the distributional dimension of equity. In this scenario, however, we remove this constraint and enable biomass imports in GCAM to assess the impact of this change.
Limited Biomass			Since biomass played a dominant role in our primary scenarios but may have negative environmental and socio-economic impacts[61,68], "limited biomass" scenarios explore the effects of limiting total biomass usage. We analyze how these constraints affect emissions reductions and the deployment of other CDR methods. Specifically, we apply biomass constraints of 1.5, 2, and 4 EJ for primary energy production in the net-zero, PCC-Q 1.5°C, and EPC-Q 1.5°C scenarios
Limited carbon storage			The total cumulative geological storage capacity for CO_2 in Canada is limited to 30 $GtCO_2$, reduced from the default value of 105 $GtCO_2$. This adjustment is important given the potential regulatory and social challenges associated with large-scale CO_2 injection[31].
Limited DAC			DAC deployment upper limits increase linearly to 30 $MtCO_2$/year by 2050 and reach 100 $MtCO_2$/year by 2100. These constraints account for the socio-political and techno-economic uncertainties, such as material supply challenges, that DAC may encounter in the coming years[32,35,69].

Scenario	Type	Burden-sharing principle	Scenario design elements and logic
Low-cost DAC			Baseline scenarios indicate a decrease in non-energy costs of DAC from 296-402 2015$/tCO$_2$ (different technology variants) to 185-230 2015$/tCO$_2$ by 2030. In low-cost scenarios, DAC costs could further decline to 78-137 2015$/tCO$_2$ by 2030. These numbers are associated with SSP5 techno-economic assumptions of DAC modeled in GCAM [70]. This scenario accounts for the future uncertainties surrounding the cost of DAC as shown by various studies[69,71].
High-cost DAC			The high-cost scenario presupposes that DAC will not experience cost reductions, maintaining current levels of 296-402 2015$/tCO$_2$. These figures align with the DAC techno-economic assumptions under SSP3[70]. The same scenario logic (exploring the uncertainties surrounding the cost of DAC) as the low-cost DAC scenario is applied here.
Limited EW			For EW potential, this analysis assumes half of the default values provided by GCAM. This limitation reflects various socio-technological barriers, including challenges related to scaling up the rock mining industry[48].
Negative Land-Use			We assume that land use will function as a CO$_2$ sink, with negative emissions from land use reaching -50 MtCO$_2$ by 2050 across all scenarios. In the EPC-Q and PCC-Q scenarios, this figure rises to -100 MtCO$_2$ in 2100 due to the stringency of the target. The assumption of -50 MtCO$_2$ by 2050 aligns with projections made in the Energy Future Canada report[22].
STC (Socio-technological change)		Three variants concerning Net-Zero 2050, EPC-Q 1.5˚C and PCC-Q 1.5	In the STC scenario, which is adapted from the sectoral strengthening scenario of Fuhrman et al.[39] several assumptions from the SSP1 "Sustainable Development" storyline are incorporated. These include limited biomass availability, a stronger preference for renewable energy, improved efficiencies in buildings and industries, lower energy demand for industrial and consumer goods [40], and a limitation on the future growth of nuclear power generation. Achieving this scenario would require transformative changes in all aspects of societal life, moving toward a more sustainable future.
STC and No-HT-DAC-NG			This scenario builds upon the elements of the STC scenario while excluding a specific type of high-temperature DAC that relies on burning natural gas for heat. This adjustment aims to further minimize dependence on fossil fuels, even when pursuing negative emissions.
EPC-Simple 1.5 ˚C		EPC simple	Under this approach, Canada incurs a carbon debt of 6.9 GtCO$_2$ based on NRCB calculated by Williges et al.[17] (See Section B3 of Appendix B for an example of such calculations). Similar to EPC-Q 1.5 ˚C, negative emissions will be scaled up, peaking by 2100. The result is available in Section B2 and Supplementary Figure 12 of Appendix B.
PCC-Simple 1.5˚C		PCC simple	Under this approach, Canada incurs a carbon debt of 79 MtCO$_2$. Similar to PCC-Q 1.5˚C, negative emissions will be scaled up, peaking by 2100. However, the 79 MtCO$_2$ carbon debt is negligible, essentially suggesting that by reducing emissions linearly to zero by 2050, there would be little to no

Scenario	Type	Burden-sharing principle	Scenario design elements and logic
			need for negative emissions. This scenario, which is essentially based on pure grandfathering (allocating the remaining carbon budget according to current emission levels), raises ethical concerns, primarily because it fails to account for historical responsibility and capacity to mitigate. The result is available in Section B2 and Supplementary Figure 12 of Appendix B.
Global 1.5 ˚C		Not applicable.	The remaining global carbon budget associated with the 1.5°C target dictates the annual global emissions constraint. This involves a linear decrease in global emissions to reach the net-zero target by 2050, followed by a linear increase in negative emissions post-2050 to align with the budget, serving as the primary constraint for the model. The result is available in Section B2 and Supplementary Figure 12 of Appendix B.

Data availability

All model output data for this study are available in a public repository accessible at https://doi.org/10.5281/zenodo.14550600

Code Availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. The particular version of GCAM is available at https://doi.org/10.5281/zenodo.7492895. Configuration files and codes used for generating the figures shown in this study are available at https://doi.org/10.5281/zenodo.14550600.

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Chapter 4

The Future of Direct Air Capture in Canada: A Systematic Scenario-Based Exploration of Barriers and Possibilities[1]

Abstract

Direct Air Capture (DAC) is increasingly recognized as a critical carbon dioxide removal (CDR) method for achieving net-zero emissions and potentially reversing end-of-century temperature overshoot. Quantitative energy-economy models often overlook the complex interdependencies, particularly socio-political factors, that shape DAC's feasibility, leading to underestimated barriers, overly simplified deployment projections, and potential misuse or underutilization of their results in real-world policymaking. To address this gap, this study applies Cross-Impact Balance (CIB) analysis—a system-theoretical scenario method that accommodates both qualitative and quantitative elements without requiring precise mathematical relationships—to systematically explore the conditions under which DAC may or may not emerge as a competitive CDR option in Canada. Based on the literature, we identified ten key descriptors affecting DAC deployment—such as clean electricity availability, DAC costs, national CDR demand, storage capacity, regulations, and public perception. Their interrelationships were assessed by experts during an in-person workshop. This expert-informed CIB analysis enables the development of internally consistent scenarios, where the mutual reinforcement of scenario factors leads to multiple stable system equilibria. Our results reveal several inter-related hard constraints that, in a Canadian context, DAC must overcome to become competitive with other CDR methods. The cost of DAC remains a significant barrier; unless technological breakthroughs or economies of scale occur to lower costs, DAC is unlikely to play a major role in future CDR portfolios. Public perception is also a key constraint—strong societal opposition, particularly around CO_2 transport and storage infrastructure, can delay or block projects. Additionally, policy coherence matters. In a fragmented regulatory environment lacking interjurisdictional cooperation,

[1] The contents of this chapter are incorporated to a paper which is under review at the *Energy Research and Social Science* journal: K. Motlaghzadeh and V. Schweizer, *"*The Future of Direct Air Capture in Canada: A Systematic Scenario-Based Exploration of Barriers and Possibilities*."*

DAC deployment is unlikely to advance meaningfully. From a national decision-maker perspective, some of these barriers, such as DAC cost, are influenced largely by global deployment and may be outside their direct control, whereas others, such as policy coherence, can be shaped by domestic policy action. By integrating expert knowledge of qualitative factors with systematic scenario analysis, this study highlights both the enabling and limiting conditions for DAC in Canada, offering guidance for its potential role in national net-zero strategies and broader global mitigation efforts.

4.1 Introduction

Carbon dioxide removal (CDR) methods include a variety of technologies, practices, and approaches aimed at capturing carbon dioxide (CO_2) from the atmosphere and permanently storing it (IPCC, 2022). These methods might play a critical role in achieving the global targets set by the Paris Agreement, supporting national net-zero pledges by offsetting residual emissions that remain after decarbonization, and potentially enabling net-negative emissions—where CO_2 sinks exceed CO_2 sources—in the future to mitigate temperature overshoot (Riahi et al., 2022). While CDR encompasses any method capable of achieving net-negative CO_2 emissions over its operational lifecycle, each CDR method is distinguished by its unique biophysical characteristics, technological readiness, system requirements, and socio-political as well as techno-economic attributes (Fuss et al., 2018). One CDR method that has garnered considerable attention from governments (Low et al., 2024) and the private sector (Wang et al., 2024) is direct air capture (DAC). DAC removes CO_2 from ambient air through chemical processes, after which the captured CO_2 can either be stored permanently (referred to as direct air carbon capture with storage, or DACCS) or utilized in various applications (direct air carbon capture with utilization, or DACCU).

Despite the growing momentum surrounding DAC, the future prevalence of this technology remains uncertain, with significant barriers and challenges complicating its potential role in addressing climate change. These uncertainties span biophysical and socio-economic dimensions, including the scale of demand for CDR, future costs of the DAC and other CDR methods, access to clean energy sources for powering DAC systems, societal acceptance of the technology, and the availability of sufficient and viable geological pore space for CO_2 storage (Erans et al., 2022; Motlaghzadeh et al., 2023). These factors are deeply interconnected, forming complex relationships that further obscure the path forward for DAC deployment. For instance, public acceptance of DAC might be influenced by its currently high costs—ranging from $400 to $3,000 per ton of net CO_2 captured (Young et al., 2023). In a survey

conducted by Sovacool et al. (2022), some experts expressed concern about the technology's heavy reliance on public funding and the risk that costs may not decrease over time, potentially straining public finances and undermining social acceptability. Additionally, DAC's substantial energy requirements introduce further complications (Chatterjee & Huang, 2020). Studies suggest that DAC could generate negative externalities by competing with other energy uses—diverting clean energy from more immediate and impactful applications that offer greater direct emissions reductions. This competition could drive up energy prices, disproportionately affecting households and potentially reducing public acceptance of the technology (Scott-Buechler et al., 2024). While the cost of DAC can shape how the public perceives the technology, public perception itself also feeds back to influence the cost of DAC. For instance, if DAC is widely unpopular within a community, project developers may face increased costs related to obtaining permits and constructing facilities, due to heightened opposition and project delays. In the U.S., there have already been cases where public resistance has halted carbon transportation pipelines, resulting in significant setbacks (MacPherson, 2025). This interplay between system elements such as cost, energy requirements, and public acceptance highlights the complex and interdependent uncertainties surrounding DAC—where changes in one dimension can significantly influence others. These are just a few examples among many possible factors shaping DAC's deployment.

While the interplay of various factors makes the future of DAC uncertain, these challenges should not prevent decision-makers from considering its potential through a robust and forward-looking lens. As part of a broader portfolio of CDR methods, DAC could play a crucial role later in the century, warranting careful planning and strategic integration into climate mitigation strategies. One effective way to understand the systemic interdependencies, envision plausible futures, and incorporate these insights into decision-making is using qualitative and quantitative scenarios. Scenarios are internally consistent representations of how a system might evolve under varying conditions (Mahmoud et al., 2009), offering a structured approach to explore uncertainties and interactions among key variables. Using scenarios for complex systems like DAC offers several advantages. Scenarios help decision-makers avoid the pitfalls of overprediction (Schoemaker, 1995)—where DAC is seen as achieving massive advancements and being a "silver bullet" for meeting climate targets—and underprediction (Schoemaker, 1995)—where DAC is dismissed due to its current costs and energy requirements, leading to the assumption that it will fail to play a significant role. By employing scenarios, decision-makers are encouraged to consider a broader range of possible futures, including those they might

otherwise overlook (Chermack, 2004). Moreover, socio-environmental systems often include variables that are challenging to model or quantify, such as public perception of DAC as a technology. The good news is that certain scenario-building approaches can effectively incorporate both qualitative and quantitative system variables, allowing for a more comprehensive exploration of these complex systems through the use of narratives or storylines (Ernst et al., 2018; Prehofer et al., 2021; Schweizer & Kriegler, 2012; Schweizer & Kurniawan, 2016). Collaborative scenario-building, where experts from diverse fields come together to co-create and refine scenarios, further enhances their value by integrating regional and multidisciplinary perspectives and fostering a shared understanding of complex systems. Collaborative scenario-building has been applied to various socio-environmental systems, including the energy and net-zero transition (Bailie et al., 2023; Kurniawan et al., 2022; Moallemi & Malekpour, 2018; Schmid & Knopf, 2012; Venturini et al., 2019; Wachsmuth et al., 2023), land-use change (Asante-Yeboah et al., 2024; Malek & Boerboom, 2015; Patel et al., 2007; Volkery et al., 2008) and carbon capture and storage (Mota-Nieto & García-Meneses, 2024).

As discussed, a portfolio of CDR methods, potentially including DAC, will be essential for achieving net-zero emissions and addressing temperature overshoot through negative emissions beyond net zero. Canada, which has set a net-zero greenhouse gas emissions target for 2050, plans to offset its residual emissions with CDR technologies. Previous modeling studies have projected different plausible deployment pathways for DAC. Canada Energy Regulator (2023) estimated a DAC contribution of 44–55 $MtCO_2$ by 2050. Navius Research (2021) found that in all scenarios where DAC is assumed to be available, it plays a significant role in achieving net-zero emissions, with removal ranging from 307 to 426 $MtCO_2e$ in 2050. Bailie et al. (2023) projected a more modest DAC deployment of 5.4–9.8 $MtCO_2$ by 2050. Motlaghzadeh et al. (2025) explored the role of diverse CDR methods not only in reaching net zero by 2050 but also in contributing to global burden-sharing efforts aimed at reversing temperature overshoots. Their findings suggest that while DAC's role in 2050 may be limited to around 50 $MtCO_2$, its contribution could increase significantly in the longer term. When considering international burden-sharing mechanisms, DAC deployment in Canada could scale up to 350 $MtCO_2$ of removal by 2100.

While quantitative models have highlighted the potential role of DAC and the uncertainties surrounding its deployment, this study seeks to explore the systemic interactions that shape its feasibility. In other words, our aim is to understand the socio-political and techno-economic barriers that may hinder or enable the deployment of DAC at the levels projected by various quantitative models.

To achieve this, we organized a workshop with experts spanning key dimensions of DAC, including economics, technology, energy transition, policy, and carbon storage. Through expert elicitation, we examined how different factors of the DAC system interact and influence one another. These insights were then used to construct plausible scenarios for DAC in the Canadian context using the Cross-Impact Balance (CIB) method, which is a system-theorical approach capable of handling both qualitative and quantitative descriptors while leveraging knowledge from diverse disciplines (Weimer-Jehle, 2006, 2023). Scholars have used CIB to bridge the knowledge originated from multiple disciplines and apply it to different domains, such as the global socio-technical scenarios for climate change research (Schweizer, 2020; Schweizer & Kriegler, 2012; Schweizer & O'Neill, 2014), socio-technical energy and decarbonization scenarios (Kurniawan et al., 2022; Pregger et al., 2020; Prehofer et al., 2021; Schuch et al., 2024; Vögele et al., 2017; Weimer-Jehle et al., 2016, 2020) and climate change adaptation (Lazurko et al., 2022; Wachsmuth, 2015). In essence, this study examines the multidimensional future of DAC within the Canadian context, constructing plausible, contextually relevant scenarios tailored to Canada's unique systems and challenges. By examining scenarios in which DAC succeeds or fails, we can identify the barriers and constraints the technology may face, as well as the opportunities that could support its deployment.

The paper is structured as follows: 4.2 describes the CIB methodology, including the process of gathering inputs and validating scenarios through two workshops. Section 4.3 presents the scenario outcomes of the study, and Section 4.4 discusses the findings, as well as their research and policy implications.

4.2 Methods

4.2.1 Scenarios, system descriptors and their variants

The CIB method is a semi-quantitative approach used to generate internally consistent scenarios by systematically analyzing interactions among key system drivers, referred to as descriptors (Weimer-Jehle, 2006, 2023). These descriptors represent essential socio-political, technological, and economic elements that influence the evolution of a system through their mutual interdependencies. Descriptors can be identified through a structured literature review, expert consultation (e.g., workshops), or self-elicitation by the core research team. The process for selecting descriptors should focus on identifying elements that strongly influence system behavior, clarifying key cause-effect relationships essential to

understanding system dynamics, and emphasizing fundamental system components rather than attempting to capture every detail.

Once the descriptors are defined, the next step is to specify alternative and plausible future states that each descriptor might take. In CIB, such alternative states are called "variants". To ensure analytical clarity, each set of variants must meet two key criteria. First, they must be comprehensive, meaning they should span the full spectrum of plausible future developments for the descriptor so that no significant possibility is excluded. Second, they must be mutually exclusive, ensuring that any real-world outcome aligns with only one variant and avoiding conceptual overlap. For example, if the cost of DAC is identified as a descriptor, its variants might be defined as ranges for "low," "moderate," and "high"—each precisely described to minimize ambiguity and to support reliable expert judgment.

In CIB, scenarios are defined as unique combinations of descriptor variants. For instance, a CIB model with three descriptors each having three variants yields 27 (3^3) possible scenarios. However, only a subset of these may be internally consistent, depending on the nature of the interactions among descriptors. By structuring the system in this way, CIB facilitates the systematic exploration of how different combinations of descriptor variants may reinforce or contradict one another, thereby identifying which system configurations represent stable, internally consistent outcomes and which do not.

At the initial stage of this project, we conducted an extensive review of the literature on various aspects of DAC, including projected demand from modeling studies (Motlaghzadeh et al., 2023), techno-economic factors (Barahimi et al., 2023), and Canada's policy and regulatory environment (Cortinovis et al., 2024). Based on these reviews, we identified ten key descriptors of the DAC system in Canada with their possible trends or variants. Table 4-1 presents the ten descriptors, along with their variants. More information about each of these is available in Section 1 of the Appendix-C.

Table 4-1. CIB descriptors and their variants for the direct air capture system

Descriptor	Description	Low Variant	Medium Variant	High Variant
A. Supply of Low-Carbon Electricity Inputs	Availability of clean energy (e.g., hydro, solar, wind, nuclear) to power DAC systems, including grid capacity and infrastructure.	Growth <1%/year (the historical rate is 1%/year)	Growth 1-3%/year	Growth >3%/year
B. Usable Pore Space	Access to and regulation of geological storage capacity for CO_2 including legal frameworks and storage hub development.	<3 $MtCO_2$/year of growth (below the lower bound of developing pore space set by the Canadian government)	3-15 $MtCO_2$/year of growth	>15 $MtCO_2$/year of growth (above the upper bound of developing pore space set by the Canadian government)
C. Availability of Other DAC Inputs	Access to non-electricity inputs such as sorbents, fuels, heat, and water, depending on DAC technology.	The availability of at least one critical input (other than electricity) is low	(No medium variant)	Availability of all DAC inputs (other than electricity) is abundant
D. Carbon Pricing	Carbon tax or credit systems influence the financial viability of DAC technologies.	Carbon tax increases no more than $10/ton/year to 2050, then $5/ton to 2075	Carbon tax increases $10-30/ton/year to 2050, then $15/ton to 2075	Carbon tax increases $30/ton/year to 2050, then $15/ton to 2075
E. Cost of DAC	Capital and operational costs of DAC systems and how they decline with investment and technological learning.	$232/ton in 2025, declining 4%/year	$232-550/ton in 2025, declining 1.6-4%/year	>$550/ton in 2025, declining 1.6%/year (similar to learning rate for nuclear power)
F. Market Demand for Products Utilizing Captured CO_2	Potential for captured CO_2 to be used in products (e.g., fuels, chemicals), influencing DAC scalability.	<3 $MtCO_2$/year utilized in Canada by 2075	3-5 $MtCO_2$/year utilized in Canada by 2075	>5 $MtCO_2$/year utilized in Canada by 2075
G. National CDR Demand	The scale of carbon removal required domestically based on emissions pathways, climate goals, and international markets.	<100 $MtCO_2$/year removed by 2075	100-400 $MtCO_2$/year removed by 2075	>400 $MtCO_2$/year removed by 2075
H. Competitiveness of DAC relative to other CDR options	DAC's performance relative to other CDR methods in terms of cost, co-benefits, permanence, and other criteria.	DAC compares poorly to other CDR options	DAC compares equally to other CDR options	DAC compares favorably to other CDR options
I. Public Perception of DAC	Public awareness, acceptance, or opposition to DAC projects, especially in local contexts.	Oppositional or polarizing; significant opposition limits DAC deployment	Neutral impact overall; public resistance does not limit DAC deployment	Supportive; widespread public acceptance of DAC

Descriptor	Description	Low Variant	Medium Variant	High Variant
J. Policy Coherence and Cooperation	Coordination among federal, provincial, and international actors affecting DAC deployment and regulation.	Highly fragmented; low inter-jurisdictional cooperation	Partial cooperation among jurisdictions by 2075	Highly integrated and cooperative regulatory environment by 2075

4.2.2 Workshop 1: Understanding the Interdependencies of the DAC System

CIB analysis captures interactions between descriptors by using influence judgments to assess how one variant affects another. These judgments are organized in a cross-impact matrix utilizing impact-balance calculations to evaluate the internal consistency of different variant combinations. The main question guiding CIB is: "Given that descriptor X has the variant X1, how does this condition influence descriptor Y to have the variant Y1?" (Weimer-Jehle, 2023) This is a pairwise relationship: For instance, if DAC follows a low-cost trajectory, how would this condition directly influence public perception to be low, medium, or high, respectively? Experts were instructed to record their judgments either qualitatively or numerically, selecting one of seven influence levels as shown in Table 4-2.

Table 4-2. Numerical and qualitative judgements in CIB

Numerical Influence	**Qualitative Description**
-3	Very strongly hindering (-VS)
-2	Strongly hindering (-S)
-1	Weakly hindering (-w)
0	No direct influence
1	Weakly promoting (+w)
2	Strongly promoting (+S)
3	Very strongly promoting (+VS)

The research team convened a DAC Canadian scenario workshop in Ottawa on September 29, 2023 bringing together 27 interdisciplinary experts from industry, academia, non-profit organizations, and government to explore the complex factors influencing the future of DAC in Canada. We leveraged our network of DAC experts and also asked participants to recommend additional experts who might be interested in the workshop. Our initial list included more than 60 individuals, and approximately 27 of

them responded and expressed interest in attending. More information about the experts and workshop instruments can be found in Table 1 of the Appendix-C.

Experts with relevant domain knowledge were invited to assess the influence of one or two descriptors within their areas of expertise. In total, 35 worksheets were completed, covering all descriptors identified for the analysis. To ensure the clarity, relevance and robustness of the judgments, several measures were implemented. First, the process was customized by allowing each expert to review initial suggestions about which descriptors they might assess and to propose additional judgments for other descriptors within their field of expertise. To enhance reliability, at least two experts provided judgments for each descriptor, allowing for comparison and triangulation of responses. For both the direction (i.e., promoting or hindering) and the strength of influence, experts were also asked to select a corresponding confidence level on a five-point scale—ranging from very high to very low. A 'very high' confidence level indicated strong certainty in either the direction or strength of the influence (i.e., judgements that would be “accepted” in the field), while a 'very low' confidence level reflected considerable uncertainty in one or both aspects (taking a “guess”). To further ensure the quality of the input, experts were required to provide brief statements regarding the logic and reasoning behind their judgments, allowing us to understand their mental models and to verify that they focused solely on direct influences rather than indirect ones (indirect influences are automatically accounted for in impact-balance calculations). The causal relationships underlying the baseline CIB analysis are described in Section 3 of the Appendix-C and summarized in Table 2 of the Appendix-C.

4.2.3 Cross-Impact Balance (CIB) Analysis for Consistent Scenario Development

CIB is a method for evaluating the internal consistency of proposed scenarios in complex systems. It assesses the internal logical consistency of each scenario. Scenarios in CIB are comprised of different combinations of descriptor variants, which, in turn, call a specific set of systemic influences. At the core of the CIB algorithm is a formalized logic check designed to ensure the internal consistency of scenarios. Each scenario as a systemic outcome is evaluated against the specific set of systemic influences recorded in the cross-impact matrix. Such influences correspond to variant interdependencies unique to the scenario. The impact-balance calculation is a logic test that confirms whether the systematic influences called by all active descriptor variants (i.e., the selected variants within the scenario under evaluation) promote (or reinforce) the test scenario. If the impact score for a test scenario variant as a systemic outcome is not the most preferred outcome (i.e., the cumulative

influence exerted by other descriptor variants on a descriptor variant can be improved by selecting a different variant of the same descriptor), the scenario is considered inconsistent and is therefore rejected. Only scenarios free of such inconsistencies are accepted as valid solutions of the matrix. This systematic evaluation narrows the vast scenario space to a small subset of consistent scenarios, preserving the inner logic that defines high-quality scenarios. ScenarioWizard software (Weimer-Jehle, 2025) automates these checks, operationalizing the CIB algorithm to efficiently analyze up to quintillions of potential scenarios. The mathematical formulation and an example of the CIB internal consistency check are provided in Section 4 of the Appendix-C. For further details on the CIB methodology and its implementation, refer to Weimer-Jehle (2006, 2009 and 2023).

4.2.4 Workshop 2: Presenting Results and Gathering Feedback

Building on the results of the first workshop and the CIB analysis, a second online workshop was held twice—scheduled to accommodate both European and North American time zones—to gather critical expert feedback on the generated scenarios. We invited both the participants from the first workshop and new experts in CIB and DAC who had been unable to attend the previous session but had expressed interest in our work. An interactive Miro board was developed for this purpose, presenting the scenario results in three categories: DAC scenarios with low, moderate, and high competitiveness compared to other CDR methods. This format allowed experts to analyze the scenarios as a family and explore their behaviors and characteristics. For example, they were able to identify common descriptor variants in scenarios where DAC had high competitiveness and compare these to scenarios where DAC was not competitive.

To refine the scenarios generated using the CIB method, experts were invited to review and provide feedback in a structured workshop setting. Prior to the workshop, experts were provided a background document featuring further detail on the CIB method, a visualization of the full CIB matrix, and brief discussion of two resulting scenarios. During the workshop, Scenario tableaus were visually represented on a Miro board, highlighting key descriptor-variant combinations to facilitate a comprehensive evaluation. Experts were prompted with guiding questions, such as whether any scenarios seemed to be missing, whether any were surprising, and whether they had additional comments or observations. This approach encouraged open discussion to help identify gaps, inconsistencies, or unexpected insights within the scenarios.

Additionally, the input judgments from the initial workshop—defining the impact of each descriptor-variant on another—were revisited for validation. Experts were asked whether any interrelationships in the CIB matrix appeared missing or surprising and whether they had questions about the relationships captured in the CIB model. Feedback from this review process was collected through field notes to uncover potential gaps or inconsistencies in the scenarios, highlight surprising or missing interrelationships, and inform refinements to the model. This iterative process ensured the scenarios reflected both logical consistency and diverse expert perspectives, enhancing their scientific credibility and applicability for decision-making.

4.2.5 Addressing Uncertainties in Expert Judgments and Expanding Scenario Portfolios

CIB evaluates scenarios for consistency by assigning each a "consistency score," which reflects how well the systemic influences of a chosen combination of descriptors as initial conditions and their resulting variants align. A scenario is "consistent" if its set of commensurate influences does not promote any descriptor variants inconsistent with initial conditions. However, the consistency threshold in CIB analysis should be considered a soft boundary, acknowledging that scenarios with slight inconsistencies may still represent plausible futures for a variety of reasons, e.g., uncertainties in expert assessments, rounding errors from the integer rating scale, or the influence of external factors excluded from the analysis (Weimer-Jehle, 2023). Marginally inconsistent scenarios that should be investigated are those whose inconsistency value falls below a defined significance threshold. Empirical data suggest that a scenario with N descriptors can only be confidently classified as inconsistent if its inconsistency value exceeds the significance threshold of $\frac{1}{2}\sqrt{N-1}$ (Weimer-Jehle, 2023). Consequently, our analysis may benefit from including scenarios with a marginal inconsistency value of 1, as this allows us to explore which descriptors might act as limiting factors. We further examine these nuances and present the insights in Section 4.3.2. An example of such a scenario and the reason it is considered marginally inconsistent is provided in Section 5 of the Appendix-C.

In addition to considering marginally inconsistent scenarios, we observed that a few pairwise relationships among descriptors received notably different judgments from experts. These differences stemmed from the distinct mental models each expert brought to the analysis. In our baseline CIB analysis, when no consensus existed for a particular influence judgment, we either replaced the values with zeros or selected the judgment that appeared more reasonable to our team. This approach allowed the model to explore a broader range of plausible outcomes. However, to better understand how

differing mental models might influence the resulting portfolio of consistent scenarios, we also conducted an ensemble analysis. This ensemble approach incorporated:

- Three alternative judgments for how the policy coherence descriptor (J) influences the carbon pricing trajectory (D);
- Two alternatives for how DAC competitiveness (H), public acceptance (I), and policy coherence (J) affect the availability of low-carbon electricity (A);
- Two alternatives for how the availability of low-carbon electricity (A) and the availability of other non-electric DAC inputs (C) influence usable pore space (B).

Combining these alternatives resulted in 12 (3 × 2 × 2) distinct input matrices for the CIB model, each potentially generating a different set of consistent scenarios. The ensemble analysis—detailed in the Section 6 of Appendix-C—not only incorporates diverse expert perspectives and mental models, thereby expanding the portfolio of consistent scenarios, but also helps identify those scenarios that remain robust across multiple judgment variations (Lazurko et al., 2023; Schweizer & Kriegler, 2012).

4.3 Results

4.3.1 Perfectly consistent scenarios

The consistency checks on 39,366 (2×3^9) possible descriptor variant combinations identified 15 perfectly internally consistent scenarios. These 15 scenarios are presented in Table 4-3. The first row (header) displays the scenario numbers, indicating that the specifications for each scenario should be read column-wise. The subsequent rows represent the ten different uncertainties (descriptors A-J) included in our analysis. Each row contains boxes representing alternative outcomes for each descriptor (i.e., variants such as H1, H2, H3 for descriptor H, which represent the competitiveness of DAC relative to other CDR approaches). These variants are color-coded using shades of yellow, orange, and green to indicate low, medium/moderate/partial, and high levels, respectively. Since one of the objectives of our study was to explore the conditions under which DAC exhibits varying levels of competitiveness, we placed the descriptor for DAC competitiveness (H) in the first row. Scenarios were grouped into families of low (Scenarios 1-7), moderate (Scenarios 8-12), and high competitiveness (Scenarios 13-15), allowing us to easily observe how other descriptor variants align with each competitiveness level by examining the rows below. The ordering of subsequent rows is based on descriptors with consistent variants across each DAC competitiveness level. Such ordering highlights co-occurring conditions

across descriptors and points of divergence. For example, in Scenarios 1–7, where DAC competitiveness is low (H1), public perception of DAC (descriptor I) is also consistently low (I1).

Since one of our key goals is to understand the barriers and constraints DAC may face, we begin by examining the system characteristics under which DAC exhibits low competitiveness relative to other CDR methods. Specifically, we focus on the seven scenarios (S1–S7) where DAC is the least competitive (H1). In these scenarios, several limiting factors frequently co-occur, creating conditions in which DAC struggles to scale. Public perception (I) is consistently low (I1), suggesting that societal skepticism or opposition poses a significant barrier to DAC deployment, which can be traced through scenario logics of these seven scenarios. Moreover, policy coherence and interprovincial cooperation regarding DAC (J) are also consistently low (J1), indicating that a fragmented policy environment and the absence of a supportive regulatory framework prevent DAC from becoming highly competitive. This is particularly important for DAC, which requires both thermal and electrical energy to operate, as well as suitable storage media for permanent CO_2 sequestration. However, these resources are unevenly distributed across the country and often do not co-exist within the same region, making interregional CO_2 transportation or electricity transmission necessary—activities that depend on a coordinated regulatory environment.

However, the value of the CIB analysis goes beyond identifying unilateral relationships. It enables us to explore more nuanced, system-wide interactions and underlying influences among descriptors. For instance, in the case of these scenarios, one can ask not only how low public perception and poor policy coherence contribute to DAC's low competitiveness, but also why these conditions arise in the first place—revealing deeper dynamics that shape the system. In the case of public perception, our experts' mental models highlight several key causal relationships. First, the high cost of DAC (as seen in scenarios S1–S6) tends to undermine public perception of the technology, fostering oppositional or polarized attitudes as people become concerned about its financial burden and develop unfavorable positions toward it. Second, experts emphasized that coherent policy can demonstrate leadership, thereby fostering positive public perception, whereas its absence (S1–S7) has the opposite effect, amplifying polarization and opposition. Finally, the low competitiveness of DAC itself creates a reinforcing loop with public perception. Public perception not only shapes DAC's competitiveness, but DAC's competitiveness also feeds back into how people perceive the technology. For example, in scenarios S1–S6, experts believed that low DAC competitiveness would lead people to question the

need for DAC, especially when other CDR options are viewed as more effective, thereby further lowering public support.

In 6 out of the 7 scenarios where DAC competitiveness is low (H1), the growth rate of available pore space for CO_2 storage is also low (B1); only Scenario 7 features a moderate growth rate. Limited pore space directly constrains DAC competitiveness, as not all CDR methods depend on geological storage—alternatives like afforestation/reforestation, enhanced rock weathering, biochar, and marine-based removals do not. Although other factors such as the availability of low-carbon electricity, national CDR demand, and carbon pricing also influence pore space availability (as discussed in Section 3 of the SI.), the variation in their levels across scenarios suggests that the common descriptors exert the strongest influences as limiting factors.

Now, turning to the scenario family where DAC becomes an important and competitive component of the CDR portfolio (H3), we examine the relevant system descriptors, their interdependencies, and the factors that would enable the technology to overcome the barriers in the H1 scenarios. A key enabler is the low cost of DAC (E1), observed consistently across all three H3 scenarios (S13–S15). This cost reduction appears to be driven by several factors: the high availability of pore space for CO_2 storage (B3), abundant DAC inputs such as heat, materials, and water (C2), a strong supply of low-carbon electricity (A3), which is very important for an energy-intensive technology like DAC, and a highly competitive DAC technology for CDR (H3), which reinforces greater deployment and learning-by-doing effects. While DAC costs are largely shaped by global deployment trends and technological learning, our findings suggest that national-level conditions can also influence cost trajectories. Notably, in these scenarios where DAC costs are already low, a high carbon price is not necessary to support its competitiveness. This is reflected in the fact that none of the perfectly consistent H3 scenarios (S13–S15) feature a high carbon price; instead, all maintain a medium trajectory (D2) consistent with the Pan-Canadian Approach to Carbon Pollution Pricing as of 2024.

Another barrier overcome in the H3 scenarios is the availability of pore space. While it was limited in the H1 scenarios (B1), it is high in the H3 scenarios (B3). Although the available pore space influences several other system descriptors—such as cost and DAC's competitiveness—it is also shaped by various system elements. For example, a medium level of carbon pricing (D2) can incentivize decarbonization across multiple sectors, with carbon capture and storage playing a particularly important role. Such pricing levels would also encourage the expansion of pore space for CO_2 storage.

Similarly, a moderate to high national demand for CDR could justify greater investment in CO_2 storage infrastructure, given the practical limitations of storage-independent approaches such as afforestation and enhanced weathering, which are constrained by their substantial land-use requirements. Together, these factors help explain why pore space availability improves under the H3 scenarios, enabling DAC to play a more competitive role in the CDR portfolio.

Finally, in the H3 scenarios (S13 to S15), the socio-political environment surrounding DAC deployment—captured by the descriptors of public perception (I) and policy coherence (J)—improves markedly compared to the H1 scenarios. Public perception is not a barrier to DAC deployment, being either neutral (i.e., not a source of major project delays, as in S13 and S14) or supportive (i.e., high public acceptance). In the latter case, widespread public acceptance facilitates or accelerates DAC deployment, potentially due to perceived co-benefits such as addressing local community needs, enabling renewable energy expansion, or aligning with environmental sustainability principles such as a circular economy or climate restoration. Similarly, policy coherence is not low (a highly fragmented regulatory environment in 2075, with DAC and carbon storage regulated differently across provinces), instead reflecting partial coherence (some inter-jurisdictional cooperation by 2075, as in S13–S14) or even to high coherence (a unified or highly integrated regulatory environment with strong inter-jurisdictional collaboration, as in S15). These outcomes stem from lower DAC costs and medium to high national CDR demand, necessitating coordinated policy efforts to meet this demand. Furthermore, as discussed in Appendix-C, experts provided judgements that public perception and policy coherence are mutually reinforcing. For instance, strong public support for DAC can incentivize policymakers to develop harmonized regulations, while the presence of clear and robust regulatory frameworks may enhance public trust and acceptance by improving understanding of the technology's risks and benefits.

Among the internally consistent scenarios, some are relatively easy for decision-makers or experts to conceptualize, even without systematically exploring interdependencies. Scenario 1 and Scenario 15, for instance, represent two clear extremes in the favorability of DAC technology. Scenario 1 depicts a highly unfavorable environment, where DAC faces significant barriers: limited access to low-carbon electricity and DAC inputs, low carbon pricing, high costs, minimal market demand, and an unsupportive policy landscape. In contrast, Scenario 15 presents the most favorable conditions for DAC deployment, characterized by abundant low-carbon electricity, high availability of DAC inputs and pore space, low DAC costs, strong policy coherence, and high public acceptance. These two scenarios intuitively align with common expectations about DAC's feasibility in different contexts. However, the

strength of the CIB approach lies in its ability to reveal less intuitive yet internally consistent scenarios, expanding the space of plausible futures beyond those that are immediately imaginable. Scenario 6 and Scenario 13, discussed below, exemplify this advantage.

Table 4-3 . Scenario tableau of the perfectly consistent scenarios for Canadian DAC system

Descriptor	Scenarios														
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
H. Competitiveness of DAC relative to other CDR options	H1							H2					H3		
I. Public Perception of DAC	I1							I2							I3
J. Policy Coherence and Cooperation	J1							J2							J3
D. Carbon Pricing	D1		D2				D3	D1		D2		D3		D2	
E. Cost of DAC	E3				E2								E1		
C. Availability of Other DAC Inputs	C1							C2							
B. Usable Pore Space	B1						B2	B1		B2				B3	
G. National CDR Demand	G1		G2				G3	G1		G2		G3	G2		G3
F. Market Demand for Products Utilizing Captured CO_2	F1				F3		F2	F1		F2				F3	
A. Supply of Low-Carbon Electricity Inputs	A1		A2		A3	A2	A3		A2		A3		A2		A3

Legend
Low
Moderate/Medium/Partial
High

- **Scenario 6: Limited Competitiveness of DAC in Canada's CDR Portfolio**

This scenario describes a Canadian DAC landscape where multiple favorable developments are insufficient to make DAC a moderately or highly competitive CDR option. Key advantages include high availability of low-carbon electricity (A3) and non-electricity DAC inputs (C2), a moderate carbon pricing trajectory consistent with Canada's current incremental carbon pricing plan (D2), a moderate cost trajectory for DAC (E2), strong market demand for captured carbon products (F3), and moderate national demand for CDR (G2). However, as shown through the logic presented in Table 4-4, three major system conditions constrain DAC's competitiveness. This table presents the impact matrix for the active descriptor variants in Scenario 6. The values range from -3 (strongly hindering) to +3 (strongly promoting), as defined in Table 4-2, and represent the influence of the active variant of the row descriptor on the active variant of the column descriptor. In addition to the numerical presentation of the direction (promoting versus hindering) and strength of the influence, color shading is also used. Green represents promoting effects and red represents hindering effects, with darker shades indicating stronger influences.

First, as shown in column B of Table 4-4, some scenario factors hinder a low-trajectory of pore space expansion—specifically, a medium carbon pricing trajectory (D2) and moderately decreasing DAC technology costs (E2), indicated by negative values of –2 and –1, respectively. In contrast, social opposition to DAC (I1) and the absence of coordinated policy (J1) promote a low trajectory, indicated by positive values of +3 and +3. Furthermore, DAC's low competitiveness (H1) relative to other CDR options further discourages pore space expansion and reinforces the low-trajectory outcome, since DAC is one of the few CDR methods that requires storage. Overall, the balance of scenario descriptors pushes the system toward a low-trajectory outcome.

Second, looking more closely at direct influences on the competitiveness of DAC (Column H), some scenario factors typically justify enhanced DAC competitiveness—namely high market demand for products utilizing captured CO_2 (F3) and a moderate cost trajectory for DAC (E2). However, the low availability of pore space (B1) for the reasons stated previously combined with the socio-political challenges of low public acceptance (I1) and lack of policy coherence (J1) in a vicious cycle diminishing the competitiveness of DAC.

Third, some scenario factors typically justify enhanced policy coherence for DAC—namely moderate national CDR demand (G2) and levels of carbon pricing at least as ambitious as the 2024 Pan-Canadian Approach to Carbon Pollution Pricing. However, the high market demand for carbon utilization (F3) might lead policymakers to wait-and-see whether additional policies are truly needed. Combined with low public perception of DAC technology (I1) and its low competitiveness compared to other CDR approaches in the scenario (H1), a fragmented regulatory landscape (J1) characterized by weak inter-jurisdictional cooperation is reinforced.

As we observed, low public perception (I1) persistently influences other descriptors. It is therefore worth examining how I1 itself is reinforced by other descriptors in this scenario. Looking at column I in Table 4-4, three influences can be identified: two moderately reinforcing effects—fragmented policy coherence (J1) and the low competitiveness of DAC (H1)—and one moderately hindering effect, stemming from a moderate level of market demand for CCUS products, as people perceive the value of DAC outputs. Overall, the reinforcing effects outweigh the hindering influence and strengthen I1. For this scenario to remain consistent, the influences on I2 and I3 must be weaker and can be confirmed by the consistency check discussed in Section 4 of the Appendix-C.

Table 4-4. Summary impact table of scenario 6

Row descriptor and its active variant		Target (column) descriptor and its active variant (short name)									
Descriptor	**Variant**	**A3**	**B1**	**C2**	**D2**	**E2**	**F3**	**G2**	**H1**	**I1**	**J1**
Supply of Low-Carbon Electricity Inputs	**A3 – High**			3		1					
Usable Pore Space	**B1 – Low**				-1	-1	1		3		
Availability of Other DAC Inputs	**C2 – High**		-1						-1		
Carbon Pricing	**D2 – Medium**	1	-2				2	2			-1
Cost of DAC	**E2 – Medium**		-1				-1		-1		
Market Demands for Products Utilizing Captured CO_2	**F3 – High**			1	1	1		1	-2	-2	1
National CDR Demand	**G2 – Medium**		1		2						-2
Competitiveness of DAC relative to other CDR options	**H1 – Low**		2	-1		1				2	3
Public Perception of DAC	**I1 – Low**		3						3		3
Policy Coherence and Cooperation	**J1 – Low**		3	-1			-1		1	2	

Legend	
-3	Very strongly hindering (-VS)
-2	Strongly hindering (-S)
-1	Weakly hindering (-w)
0	No direct influence
1	Weakly promoting (+w)
2	Strongly promoting (+S)
3	Very strongly promoting (+VS)

- **Scenario 13: The Minimum Conditions for High DAC Competitiveness**

This scenario illustrates a future in which Canada follows a moderate CDR demand trajectory (G2), and DAC plays a significant role in the CDR portfolio due to its high competitiveness relative to other CDR methods (H3). As shown in Table 4-5, this high competitiveness is primarily driven by DAC's low-cost trajectory (E1), with additional—but weaker—influences from the high availability of DAC inputs such as high availability of pore space (B3), of heat and materials (C2), and partial policy coordination (J2). Table 4-5 further highlights the drivers behind DAC's low-cost trajectory. It is strongly promoted by high pore space availability (B3), abundant DAC inputs (C2), and a high supply of low-carbon electricity (A3), as well as a weakly reinforcing influence from DAC's competitiveness (H3), likely reflecting economies of scale and learning-by-doing. However, this trajectory is slightly hindered by neutral public perception (I2), which might temper enthusiasm or slow deployment to some extent. Despite this, the cumulative promoting influences reinforce the low-cost trajectory for DAC and clearly outweigh the hindering effects.

Turning to the drivers of high pore space expansion (B3), we observe a cumulation of weak promoting influences from the availability of DAC inputs (C2), low cost of DAC (E1) and DAC's high competitiveness (H3). On the other hand, moderate national CDR demand (G2)—which may be met largely through storage-independent CDR methods—and the lack of a fully coordinated DAC policy (J2) somewhat hinder the expansion of pore space. Nevertheless, the net effect of the promoting descriptors (C2, D2, E1, H3) outweighs the hindering ones (G2, J2), resulting in a high pore space expansion trajectory.

The key takeaway from this scenario is that a successful future for DAC does not necessarily require a highly coordinated policy landscape or widespread public support. Instead, technological progress, cost reductions, and readiness of storage infrastructure appear to be the primary enablers provided that efforts are also made to support a balanced public perception of DAC as well as sufficient partial policy coherence that does not stymie DAC projects or their scale-up as needed.

Table 4-5. Summary impact table of scenario 13

Row descriptor and its active variant		Target (column) descriptor and its active variant (short name)									
Descriptor	**Variant**	**A3**	**B3**	**C2**	**D2**	**E1**	**F2**	**G2**	**H3**	**I2**	**J2**
Supply of Low-Carbon Electricity Inputs	**A3 – High**			3		2					
Usable Pore Space	**B3- High**					3			1		
Availability of Other DAC Inputs	**C2 – High**		1			3			1		
Carbon Pricing	**D2- Medium**	1	1				-1	2			1
Cost of DAC	**E1- Low**		1	1			1	1	2	1	
Market Demands for Products Utilizing Captured CO_2	**F2- Medium**			1						1	
National CDR Demand	**G2-Medium**		-1		2						1
Competitiveness of DAC relative to other CDR options	**H3-High**	1	1			1				1	1
Public Perception of DAC	**I2- Moderate**					-1					1
Policy Coherence and Cooperation	**J2- Partial**		-1	1			2		1		

Legend	
-3	Very strongly hindering (-VS)
-2	Strongly hindering (-S)
-1	Weakly hindering (-w)
0	No direct influence
1	Weakly promoting (+w)
2	Strongly promoting (+S)
3	Very strongly promoting (+VS)

4.3.2 Marginally inconsistent scenarios

As discussed in 4.2.5 (Methodology), the soft boundary of consistency thresholds allows scenarios with small inconsistencies to remain relevant, accounting for uncertainties in expert assessments and external influences considered beyond the scope of the analysis. Including marginally inconsistent scenarios expanded the scenario set to 39, of which 15 are perfectly internally consistent. Among the 24 new scenarios, 9 exhibit high DAC competitiveness, 5 moderate competitiveness, and 10 low competitiveness. The scenario tableaus for these cases are provided in Tables 6, 7, and 8 of the Appendix-C.

Here, we briefly highlight two notable scenarios that emerged in the extended consistent set. Scenario 12 of the extended portfolio (shown by EX12 in Table 6 of the Appendix-C), a marginally inconsistent scenario, presents even more favorable conditions for DAC deployment than Scenario 6 that we discussed in the previous section, yet DAC remains uncompetitive. Both scenarios feature high availability of low-carbon electricity (A3) and non-electricity DAC inputs (C2), as well as moderate improvements in DAC costs (E2). However, Scenario 12 has additional advantages, including higher carbon pricing (D3) and stronger national CDR demand (G3). Unlike Scenario 6, which is constrained by low pore space availability, Scenario 12 benefits from medium pore space availability (B2), reducing one of DAC's key limitations. Nevertheless, despite these advantages, DAC fails to gain competitiveness due to strong public opposition (I1-Low) and a fragmented regulatory environment (J1-Low). This scenario underscores that even with improved storage conditions and stronger policy incentives, non-technical barriers—particularly governance and social acceptance—can still prevent DAC from emerging as a viable CDR option. One might ask why, despite all the improvements, public acceptability and policy coherence around DAC remain low. Public acceptability is influenced by three main descriptors, most notably hindered by the low competitiveness of DAC. When people perceive the technology as unviable or unnecessary, they are less likely to support it. Furthermore, the lack of coherent policies surrounding DAC undermines public trust in its deployment. It's important to note that the cost of DAC only negatively affects public perception when it is high; once costs become low, they no longer improve perception—highlighting an asymmetric relationship. As a result, even with reduced costs, public support may remain low. Similarly, policy coherence is weakened by both low public support and low competitiveness. While a high carbon price could potentially signal greater alignment and push toward stronger policy coordination, its influence is not strong enough alone to offset the broader trend toward fragmentation.

Another scenario of interest is Scenario 39 from the extended portfolio (shown by EX30 in Table 8 of the Appendix-C), which closely resembles Scenario 15 from the perfectly consistent scenarios (Table 4-3). Both scenarios depict conditions highly favorable for a competitive DAC market. However, the key difference is that Scenario 15 assumes a medium carbon pricing trajectory (D2-Medium), while Scenario 39 follows a high carbon pricing trajectory (D3-High). The reason Scenario 39 did not emerge as perfectly consistent and is instead classified as marginally inconsistent lies in expert judgments regarding the relationship between DAC costs and carbon pricing. Experts assessed that if DAC costs are already low, it is more plausible for carbon pricing to remain at a medium level, as its primary role toward the end of the century would be to support costly technologies like DAC. Since DAC in this scenario is already cost-competitive, a high carbon price may seem unnecessary. However, in the extended scenario portfolio, Scenario 39 emerges as a potentially plausible future. One possible justification for Scenario 39 could be a situation where climate change impacts escalate beyond expectations, potentially due to unanticipated tipping points. In such a case, the social cost of carbon would be significantly higher, leading to either national or international markets implementing strong financial incentives or subsidies to remove excess atmospheric CO_2 and return concentrations to safer levels. This highlights how marginally inconsistent scenarios can help uncover alternative, yet plausible, climate mitigation pathways that might not have been initially considered in the set of perfectly consistent scenarios.

4.3.3 Exploring Mental Model Diversity via Ensemble Scenario Analysis

As discussed in 4.2.5, we used an ensemble analysis approach to account for divergent judgments in pairwise influence assessments. Some of these judgments varied significantly, so we generated 12 input matrices based on different combinations of those alternatives—one of which served as the baseline configuration on which the main analysis in this paper is based. Across all 12 consistency checks, eight scenarios were found to be common; these are presented in Table 13 of the Appendix-C. In four of these scenarios, DAC exhibited low competitiveness relative to other CDR methods (H1), corresponding to Scenarios S3, S4, S5, and S6 in the baseline set shown in Table 4-3. The remaining four scenarios showed moderate competitiveness (H2) and correspond to Scenarios S9, S10, S11, and S12 in Table 2. Notably, no single scenario with high DAC competitiveness (H3) appeared across all 12 configurations, highlighting the high sensitivity of scenario outcomes to the model inputs. The number of unique scenarios increases from 15 in the baseline case to 24 (U1 to U26 as shown in Table 14 of the Appendix-C) when considering all scenarios that appeared at least once across the 12 different

CIB input sets. These 24 scenarios include 11 with low DAC competitiveness (H1), 7 with moderate competitiveness (H2), and 6 with high competitiveness (H3). This expanded scenario portfolio provides decision-makers with a broader view of possible futures for DAC. Figure 4-1 summarizes these insights by presenting the percentage distribution of descriptor variants across each DAC competitiveness category. While this provides a high-level overview, each of the 25 scenarios can also be explored individually to understand the underlying chains of influence and system dynamics. As shown in the figure, focusing on the third row (H3), we observe that in approximately 83% of the H3 scenarios (5 out of 6 scenarios), the market demand for CO_2-based products, national CDR demand, public perception of DAC, and policy coherence around the technology are high. In the remaining 17% (1 scenario), these descriptors are at moderate levels. Notably, in all scenarios where DAC emerges as a highly competitive technology, it follows a low-cost trajectory. The availability of other key DAC inputs—such as heat, materials, pore space, and land—is consistently high across all H3 scenarios. The supply of low-carbon electricity is high in most scenarios but moderate in 33% (2 scenarios).

Another high-level analysis enabled by the CIB input matrix is the active-passive diagram, which helps identify how influential (active) or influenced (passive) each descriptor is within the system. The active sum of a descriptor is calculated by summing all absolute impact values it exerts on other descriptors (i.e., its row in the impact matrix), while the passive sum is the total of absolute impacts it receives from others (i.e., its column). Highly active descriptors strongly affect others, whereas highly passive descriptors are strongly influenced by the system—but a descriptor can be both. In our ensemble analysis using 12 input matrices, each descriptor may have up to 12 different active and passive scores. Figure 4-2 plots the passive sum (X-axis) against the active sum (Y-axis) for each descriptor across ensembles, represented by different colors and shapes. Changes in these values across ensembles—reflected by multiple points with the same shape and color—indicate the sensitivity of descriptor influences under different judgment sets. While this system grid offers a straightforward view of direct influences, more complex, indirect dynamics should be explored through scenario logic. This figure shows that the cost of DAC (E) not only has the highest active sum but also a relatively high passive sum, indicating that it is both highly influential—strongly affecting many other descriptors—and highly influenced by them. In contrast, the availability of low-carbon electricity (A), located in the bottom-left of the figure, has the lowest passive sum. This suggests that it is minimally influenced by other descriptors included in the CIB model, which focused on factors that influence DAC technology development and deployment. Moreover, the wider variation in its passive score across ensembles

reflects greater sensitivity to alternative judgments. Overall, the low passiveness score implies that the trajectory of low-carbon electricity is largely shaped by factors external to the system boundary—such as future energy regulations. Overall, the most influential descriptors—those with the highest active sum scores—are policy coherence around the technology (J1) and carbon pricing (D), as they exert strong direct influences on a wide range of other descriptors. While this provides useful insights for identifying potential intervention points that decision-makers might consider, it only captures direct influences. As noted earlier, deeper insights into more dynamic and indirect influences require exploring scenario logic. For instance, descriptors such as pore space availability and public perception, while not appearing highly influential in this plot, emerge as critical factors in scenario-based analyses.

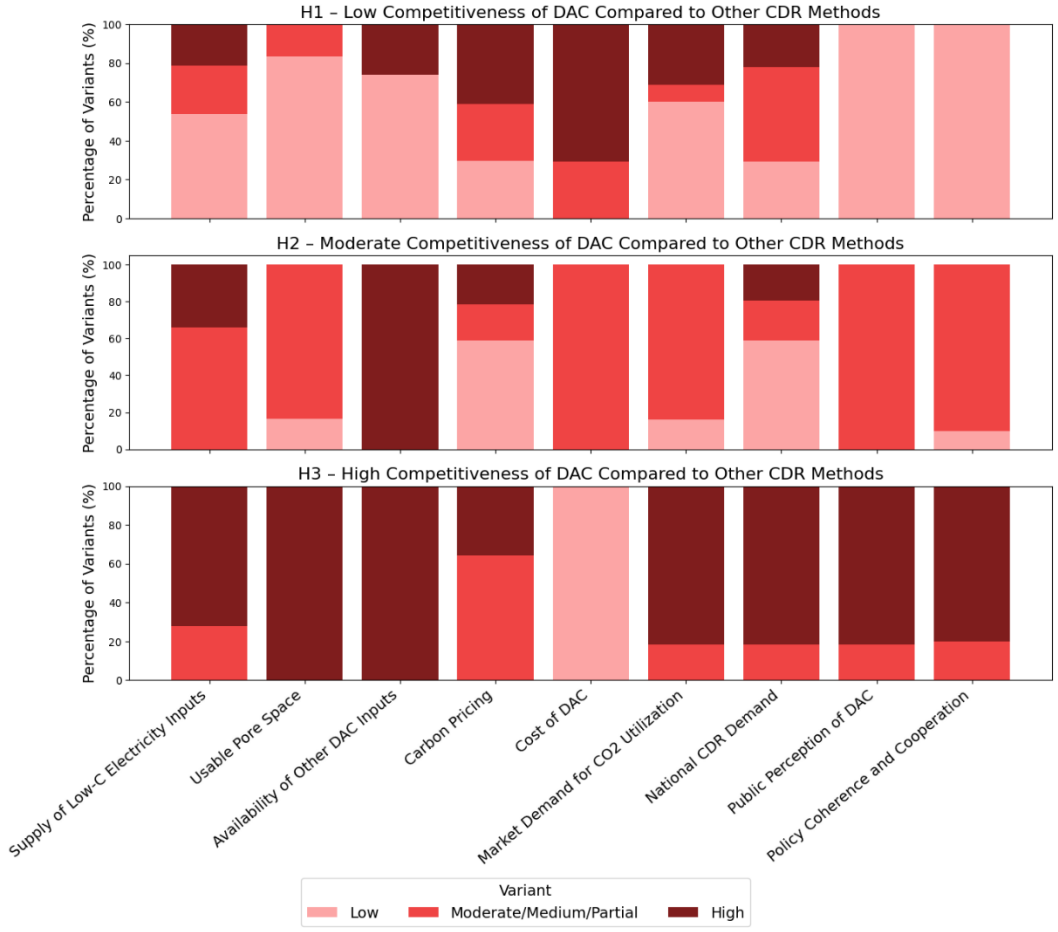

Figure 4-1. Distribution of descriptor variants across different levels of DAC competitiveness

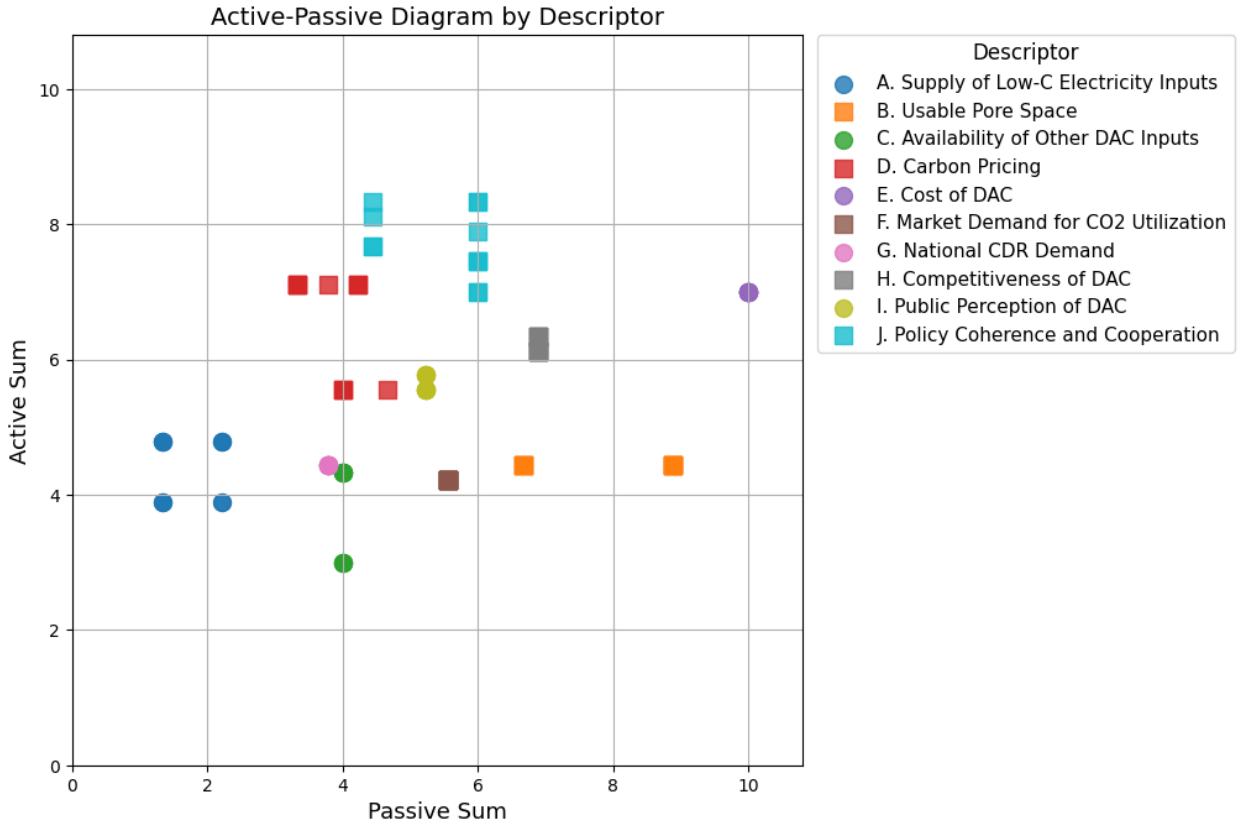

Figure 4-2. Active–passive diagram across scenario ensembles

4.4 Discussion and Conclusion

CDR is expected to play a crucial role in achieving net-zero emissions and addressing historical responsibilities, particularly for countries like Canada (Motlaghzadeh et al., 2025). While DAC is gaining attention as a promising CDR method, its future remains highly uncertain due to different socio-political and techno-economic factors (Erans et al., 2022). The future competitiveness of DAC among various CDR methods depends on the interaction of systemic factors, the nature of existing barriers, and whether supportive conditions for large-scale deployment can emerge. This study used CIB analysis—a systems-theoretical, semi-quantitative scenario-building approach—to systematically explore the conditions that could make DAC a competitive CDR option in Canada, as well as the barriers that must be addressed. CIB enabled us to incorporate difficult-to-quantify factors—such as public perception and policy coherence through interprovincial cooperation—through expert-driven

judgments on the interactions among key DAC system descriptors. To acknowledge potential differences in experts' mental models, we also conducted an ensemble analysis to capture variations in their views regarding the influences among different scenario factors. The method identified both internally consistent futures and marginally inconsistent yet plausible scenarios, illustrating a range of alternative pathways for DAC over the next 50 years. By broadening the exploration of possible futures through scenario generation, CIB helps avoid the pitfalls of deterministic thinking, which often places undue emphasis on a single outcome or an overly narrow set of possibilities. Instead, CIB provides decision-makers with a more comprehensive understanding of the uncertainties, their interactions and enabling conditions that are likely to shape DAC's potential success.

Based on our findings, DAC faces multiple interconnected barriers that must be addressed for it to become a competitive part of the CDR portfolio that Canada might deploy later in the century. One of the most immediate barriers is DAC's high capital and operational costs. Cost reductions emerged as a non-negotiable prerequisite for futures where DAC is at least moderately competitive with other CDR options. Scenarios where DAC thrived consistently featured low technology costs. These cost reductions are influenced by global factors such as technology development, learning-by-doing, and economies of scale (Sievert et al., 2024; Young et al., 2023), which fall outside the scope of this domestic analysis. Public perception also affects the DAC cost trajectory, as low public perception (defined as social opposition) can delay project implementation and drive-up costs. CIB analysis revealed that the cost of DAC, while primarily a techno-economic factor, both influences and is influenced by socio-political dynamics. For instance, as shown in Table 4-3, if DAC costs follow a low-cost trajectory (i.e., achieving a levelized cost no more than $232/ton in 2025 and averaging at least a 4% annual cost reduction), social opposition is unlikely. Based on our experts' mental model, high DAC costs can trigger public resistance, especially if DAC is perceived as an inappropriate use of taxpayer money or sparks skepticism that questions the need for such an expensive solution. Conversely, when DAC becomes more affordable, it is more likely to gain public support and can become viable under moderate carbon pricing mechanisms—such as Canada's existing carbon tax.

Another important factor is the availability of low-carbon electricity, which is consistently moderate to high across all scenarios where DAC is highly competitive. While a high supply of low-carbon electricity alone is not sufficient to guarantee DAC's competitiveness, it is a necessary condition. This is due to DAC's high energy demands—if met by carbon-intensive sources, the net carbon removal benefit is significantly reduced. Moreover, since large volumes of clean electricity are also needed for

broader decarbonization efforts, allocating it to an energy-intensive technology like DAC would be difficult to justify if supply is constrained. In scenarios with high availability of low-carbon electricity, carbon prices tended to follow a moderate-to-high growth trajectory, helping to justify the expansion of these clean energy resources.

Third, insufficient CO_2 storage infrastructure is a major barrier to DAC's competitiveness. Unlike some other CDR methods, DAC relies heavily on access to reliable, large-scale storage. In scenarios where storage was limited or poorly located, DAC could not achieve high competitiveness. This challenge is particularly significant because much of the available storage capacity is already being allocated to carbon capture and storage (CCS) from point sources, such as fossil fuel combustion and industrial processes like cement and steel production. In fact, all current and planned storage projects in Canada—particularly in Alberta and Saskatchewan—are focused on CCS. Modeling studies suggest that the storage volume required for CCS alone could be two to three times greater than what is needed for CDR methods like DAC and BECCS (Motlaghzadeh et al., 2025). While CO_2 storage will be necessary regardless of whether DAC is pursued, for DAC to become a viable and competitive option, storage capacity must exceed the demands of CCS. Within our system boundary, descriptors such as public perception of DAC, policy coherence around the technology, and carbon pricing may influence the future expansion of pore space in Canada. However, several other techno-economic and socio-regulatory factors—identified by one of our experts but falling outside our system boundary—are also critical. These include advancements in drilling technologies, pressure management practices, supportive storage regulations, diversification of sequestration methods, and public acceptance of the storage process itself.

Finally, public perception of the technology and the level of policy coherence and cooperation emerged as two of the most critical factors, yet they are often overlooked in techno-economic analyses. Even under favorable techno-economic conditions—such as reduced DAC costs, moderate demand for CDR, and sufficient availability of low-carbon electricity and other key inputs—negative public sentiment can significantly hinder DAC's competitiveness. Public concerns about land use, environmental risks, and equity issues can fuel social opposition. Securing a social license to operate is therefore essential for enabling large-scale deployment. This requires early stakeholder engagement, transparency about the purpose of carbon removal (including assurances that it will not be used to delay mitigation), clear communication of environmental risks, strategies for monitoring and managing those risks, and ongoing efforts to build and maintain public trust. Judgements from the expert panel and CIB

model results show that the impact of public perception extends beyond competitiveness: strong opposition can increase deployment costs by causing delays or halting construction and operations. Furthermore, if communities resist local DAC facilities, this may result in a fragmented policy landscape with limited cooperation across provinces—further undermining the enabling conditions for DAC to thrive. To address this, at least, some level of interprovincial cooperation, along with coherent governance across energy, industrial, and environmental sectors, are crucial. This is especially important given that DAC requires two key resources—energy and CO_2 storage space—which are not always co-located. In some provinces, an abundance of one may coincide with a scarcity of the other, reinforcing the need for coordinated planning and infrastructure development.

Our findings suggest that DAC's long-term viability and competitiveness depend on the alignment of multiple key system conditions. In the scenarios where DAC was highly competitive, success was driven by technological readiness, cost reductions, moderate or strong regulatory support, moderate or strong public acceptance, and a moderate/high level of CDR demand. The absence of any one of these factors, even under otherwise favorable conditions, significantly undermined DAC's viability. These insights underscore the need for a holistic approach to DAC policy and planning that goes beyond purely economic considerations to incorporate social, regulatory, and infrastructural factors.

Quantitative modeling approaches—such as IAMs—often fall short in capturing the socio-political, institutional, and technological complexities that influence the viability of emerging technologies like DAC (Gambhir et al., 2019). As a result, they may project unrealistic deployment levels without offering insights into the enabling conditions required for such outcomes (Schwanitz, 2013). These models often place too much emphasis on quantifiable factors such as technology costs and energy requirements, while overlooking socio-political dimensions and their complex interconnections that also shape widespread technological deployment. For the modeling community, this study offers a clear message: modeling DAC in isolation from social, institutional, and political dynamics risks producing misleading results. IAMs should be complemented with qualitative, systems-based approaches like CIB that capture feedback loops and non-linearities often overlooked in purely quantitative models. Rather than treating such socio-political uncertainty as noise to be minimized, or simply beyond model scope, it should be viewed as a signal to be explored through scenario diversity and ensemble-based methods. Future modeling efforts must recognize that "soft" variables—such as public perception and regulatory alignment—can be just as determinative of outcomes as traditional "hard" constraints like cost or energy availability.

4.5 References

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Chapter 5

Adaptation Pathways for Direct Air Capture in Canada: A Proposed Framework for Coordinating Multi-Sectoral Responses to Deep Techno-Economic and Socio-Political Uncertainty[1]

Abstract

Canada may need to rely on Direct Air Capture (DAC) later in the century to offset residual emissions and to help reverse temperature overshoot. However, deep technological and socio-economic uncertainties surrounding DAC could delay or misguide policy action. While quantitative modeling offers valuable insights into these uncertainties, it often overlooks socio-political dynamics and real-world implementation barriers. To address this gap, this study uses the Global Change Analysis Model (GCAM) to quantify future DAC demand based on a qualitative scenario analysis developed through expert-informed Cross-Impact Balances (CIB) analysis in earlier work. To connect these insights with policy, the Adaptation Pathways (AP) framework, which is a method rooted in decision-making under deep uncertainty, is applied to develop decision-support maps across three key dimensions: economic instruments (who pays for DAC), electricity supply (how to power DAC), and CO_2 storage. These AP maps identify critical decision points and outline policy packages suited to different DAC demand levels across those three dimensions. Our CIB-informed GCAM scenarios project DAC demand in 2050 ranging from 0 to 87 $MtCO_2$/year, depending on factors like mitigation success, CO_2 storage availability, advancements in other CDR methods, and DAC technology costs. For the economic dimension of DAC, we find that a very low DAC demand (less than 5 $MtCO_2$/year) may be managed under current voluntary markets, government procurement and investment tax credits. Higher demand would require more ambitious instruments such as carbon take-back mandates. Similarly, electricity-related pressures remain minimal below 5 $MtCO_2$/year but intensify with scale, potentially requiring dedicated clean energy development, grid expansion, and potentially hub-based DAC deployment. Finally, regarding the storage dimension, early-stage CO_2 captured by DAC can be stored in existing

[1] Contents from this chapter will be incorporated into a manuscript being prepared for submission to the call for papers entitled "*Adaptation Pathways and Scenarios for Climate Change Research*" with *npj Climate Action*.

or planned sites—primarily in Alberta and Saskatchewan—that are already regulated for storing emissions from point sources. However, as storage requirements grow, Canada may need to explore and enable the use of additional onshore and offshore storage sites across the country. Another key contribution of this study is the integration of three systematic scenario approaches—CIB, integrated assessment modeling with GCAM, and AP—into a novel, unified framework. This integrated approach leverages the strengths of each method to create a scientifically credible and salient decision-support tool that links deeply uncertain scenarios with real-world policy pathways.

5.1 Introduction

Carbon dioxide removal (CDR) methods, which extract and sequester carbon from the atmosphere (Babiker et al., 2022), are essential for both achieving national net-zero targets and addressing carbon debts by helping to reverse temperature overshoot. Canada, with its 2050 net-zero greenhouse gas emissions goal and relatively high historical responsibility for climate change, stemming from its higher per capita emissions compared to many other countries, may require hundreds of megatonnes of CDR deployment post-net-zero, according to previous modeling studies (Fong & MacDougall, 2023; Motlaghzadeh et al., 2025). Among various CDR approaches, direct air capture (DAC), a process that uses chemical sorbents or solvent to remove CO_2 from the atmosphere and store it underground, has been gaining increasing attention both globally and within Canada. Quantitative modeling through integrated assessment models (IAMs) suggests that DAC deployment could reach up to 400 $MtCO_2$ of removal by 2100 (Motlaghzadeh et al., 2025). Demand for DAC is highly uncertain and depends on several factors, including the extent of decarbonization achieved, which determines the level of residual emissions requiring compensation, and the potential existence of an international agreement to remove excess atmospheric carbon based on equity principles. Some studies also examine key sources of techno-economic uncertainty—such as DAC costs, storage availability, and assumptions about other CDR methods—that influence the projected scale of DAC deployment in their models (Cortinovis et al., 2024; Motlaghzadeh et al., 2023, 2025).

While IAMs can be useful and policy-relevant, they have inherent limitations, particularly in capturing socio-political dynamics, behavioral factors, and governance challenges. Many IAMs rely on cost-optimization approaches that do not fully integrate qualitative knowledge from stakeholder perspectives, social acceptability considerations, and real-world policy constraints (Ackerman et al., 2009). As a result, IAM-based projections may overestimate or underestimate DAC's feasibility by

neglecting non-technical barriers and opportunities that could shape its adoption. Addressing these gaps requires a more holistic approach that combines quantitative modeling with qualitative scenario-building methods. As an example of such efforts, Chapter 4 used Cross-Impact Balances (CIB) method, a system-theoretical scenario method developed by Weimer-Jehle (2006), to systematically explore the conditions necessary for DAC to emerge as a competitive CDR option in Canada. Through a literature review, key descriptors influencing DAC deployment were identified, including clean energy availability, cost trajectories, market and national CDR demand, storage capacity, regulatory conditions, and social acceptance. Using CIB informed by DAC experts, internally consistent scenarios reveal that DAC becomes highly competitive only under conditions of high availability of low-carbon electricity, significant cost reductions, a favorable policy and regulatory environment, an absence of public opposition, and sufficient storage infrastructure. The findings underscore that DAC deployment is not solely dependent on technological advancements or market incentives, and factors such as policy coherence and societal acceptance are equally critical.

The deployment of DAC is fraught with deep uncertainty, where both probabilities and the significance of potential outcomes remain unknown. This makes it challenging to generate precise long-term forecasts for DAC's role in Canada's net-zero and post net-zero strategies. As a result, decision-making around the technology can become either paralyzed—delaying necessary near-term actions—or misguided, leading to ill-informed choices that fail to align with how the future unfolds. One of the primary objectives of scenario analysis is to help decision-makers navigate uncertainty by identifying its sources and supporting scenario-informed decision-making. However, qualitative scenarios generated through CIB analysis and quantitative scenarios derived from energy-economy models hold limited value if they are not salient or structured in a way that policymakers can use effectively. To bridge this gap, this study utilizes the Adaptation Pathways (AP) framework (Haasnoot et al., 2012, 2024) in a novel way to connect qualitative and quantitative scenarios with sequential policies and actions. This integration allows for a systematic assessment of (i) how different policy interventions influence key objectives and (ii) how various sources of uncertainty—captured through scenarios—affect policy effectiveness.

By mapping multiple pathways and identifying critical decision points—moments when policies and actions fail to achieve their objectives under uncertainty (Marchau et al., 2019)—AP facilitates the development of flexible and adaptive strategies. These strategies can adjust to evolving conditions, stakeholder priorities, and shifting policy landscapes. AP, along with its sister method, Dynamic

Adaptive Policy Pathways (Haasnoot et al., 2013), has been widely applied to problems involving deep uncertainty, such as water resource management and planning (Carstens et al., 2019; Haasnoot, 2013; Muccione et al., 2024), transportation, sustainability (Butler et al., 2016) and agriculture and forestry (Cradock-Henry et al., 2020; Vizinho et al., 2021). A recent review of these applications found that the deployment of adaptation pathways has resulted in greater confidence among decision makers by identifying robust policy choices that remain viable under future uncertainty. Additionally, when combined with participatory processes that incorporate community values, adaptation pathways have contributed to building trust in decision-making, particularly in contexts where conflicting interests and power asymmetries exist among public and private decision agents (Haasnoot et al., 2024).

To develop a policy-relevant tool for the Canadian context that supports decision-making around DAC technology, this study combines qualitative scenarios—generated through expert-informed CIB—with quantitative modeling using the Global Change Analysis Model (GCAM), an IAM. Quantifiable elements from the CIB-derived storylines are incorporated into the GCAM-based assessment of DAC demand trajectories. In addition, we present three preliminary prototypes of AP maps—focusing on economics, electricity supply, and CO_2 storage—to illustrate how this framework can help communicate uncertainty and link near-term decisions and long-term strategies to the decision-making objective. While this chapter represents only the initial phase of a broader, ongoing research initiative, it lays the foundation for future work by developing and testing the first version of this integrated decision-support framework. Section 5.2 provides an overview of the methods used in this study. Section 5.3 presents the results of applying the methodology to the DAC challenge in Canada. Section 5.4 discusses key findings, their implications, and directions for future research.

5.2 Methodology

5.2.1 Deep uncertainty

Deep uncertainty arises when decision-makers lack knowledge of—or cannot agree on—the most appropriate system model, the key outcomes and their relative importance, or the probability of different inputs and events (Lempert, 2003; Walker et al., 2013). It also arises when decisions must be made over time in interaction with an evolving system, making them interdependent (Haasnoot, 2013; Haasnoot et al., 2013; Hallegatte et al., 2012). This leads to a wide range of plausible models, differing preferences, uncertain parameters, and multiple potential decision pathways (Kwakkel et al., 2016; Kwakkel et al., 2010). Deep uncertainty is common in socio-environmental and technological

transitions, where numerous interacting uncertainties—environmental, socio-political, and techno-economic—exist, and stakeholders often have conflicting interests (Stanton & Roelich, 2021). Under deep uncertainty, conventional decision-making approaches—like predicting outcomes before acting or maximizing expected utility—often fall short, as future impacts are hard to foresee and there is little consensus on how to evaluate or prioritize outcomes (Lempert, 2003; Stanton & Roelich, 2021). To address decision-making challenges under deep uncertainty, researchers have developed a range of methods collectively known as Decision Making under Deep Uncertainty (DMDU). These approaches, to varying degrees, support decision analysts in navigating complex, uncertain futures. Although DMDU approaches vary considerably, they generally emphasize one of two principal dimensions. Some prioritize robust strategies that perform satisfactorily across a wide range of plausible futures (Robust Decision Making), as discussed by Kalra et al. (2014) and Lempert (2019). Others emphasize adaptive strategies that can be adjusted over time as new information emerges (Adaptive Pathways / Dynamic Adaptive Policy Pathways), as outlined in Haasnoot et al. (2013). In this study, we apply the AP approach, which belongs to the latter category, to identify near-term actions for DAC decision-making in Canada that remain flexible and responsive to how the future unfolds. The AP approach is explained in the next subsection (Section 5.2.2).

5.2.2 Adaptation pathways (AP)

The AP approach, as outlined by Haasnoot et al. (2012) and illustrated in Figure 5-1 is centered around the concept of adaptation tipping points (Kwadijk et al., 2010). These tipping points refer to the conditions under which an existing policy no longer fulfills its intended objectives. The timing of these tipping points can vary depending on the scenario. Additional measures must be taken proactively, as some policies require significant time to implement. This sequence of decisions forms what is known as an adaptation pathway. The approach visualizes potential actions following a tipping point using adaptation trees, which resemble decision trees or maps for wayfinding in metro stations, where each possible route represents a different adaptation pathway (Haasnoot et al., 2013).

The steps that need to be taken for building adaptation pathways maps are shown in Figure 5-1a. Similar to any decision-making problem, the first step is to identify the objective of the analysis—for example, ensuring that DAC technology can be supplied in a sustainable and equitable manner. This step also involves understanding both the current state of the system (e.g., what are the current DAC system characteristics and how much DAC can currently be supplied) and the uncertainties surrounding

future conditions (e.g., how future situations might evolve due to various sources of techno-economic and socio-political uncertainty). Using this information, we move to Step 2: analyzing how the system performs under different future conditions, given its current capacity. In most long-term planning problems, the current system is unlikely to meet future needs under all possible conditions. Therefore, Step 3 involves identifying actions and policies that could be implemented to help achieve the objective. In Step 4, we construct scenarios that illustrate how key external drivers might evolve over time—based on the future uncertainties identified in Step 1. These scenarios capture a range of plausible futures and are critical for stress-testing potential actions. Step 5 involves testing the performance of policy options identified in Step 3. We evaluate, either logically or through computational models, under what conditions these policies might fail to meet the objective. This is where we identify "sell-by-dates" or tipping points—critical moments when a given policy no longer works under specific scenarios. For example, a DAC deployment policy may fail if demand exceeds 50 $MtCO_2$/year; this threshold might be reached in 2050 in Scenario 1 but not until 2100 in Scenario 2. Once the sell-by-dates are determined for various policy options under each scenario, we can construct an adaptation pathways map as shown in Figure 5-1b. In this map, the X-axis represents time or illustrative scenarios, and the Y-axis shows different policy options. In the adaptation pathways map, each point where a policy fails—also known as a tipping point—indicates the need to transition to an alternative option in order to continue meeting the objective. A pathway is essentially a sequence of policy options that are implemented over time in response to changing conditions. Because implementing a new option often requires lead time for planning, investment, and stakeholder coordination, the actual decision point—the moment when a new policy must be adopted—typically occurs before the tipping point is reached. This ensures that the transition can be made in time, avoiding disruptions or failures in meeting the objective (Haasnoot et al., 2013, 2024). Once different pathways have been identified, they can be assessed based on their costs, benefits, and other relevant dimensions (as shown in the Scorecard section of Figure 5-1b)—either through modeling by decision analysts or collaboratively with stakeholders. Engaging stakeholders enables the incorporation of diverse values and perspectives, which can shape both the evaluation of pathways and the selection of preferred options (Haasnoot et al., 2013).

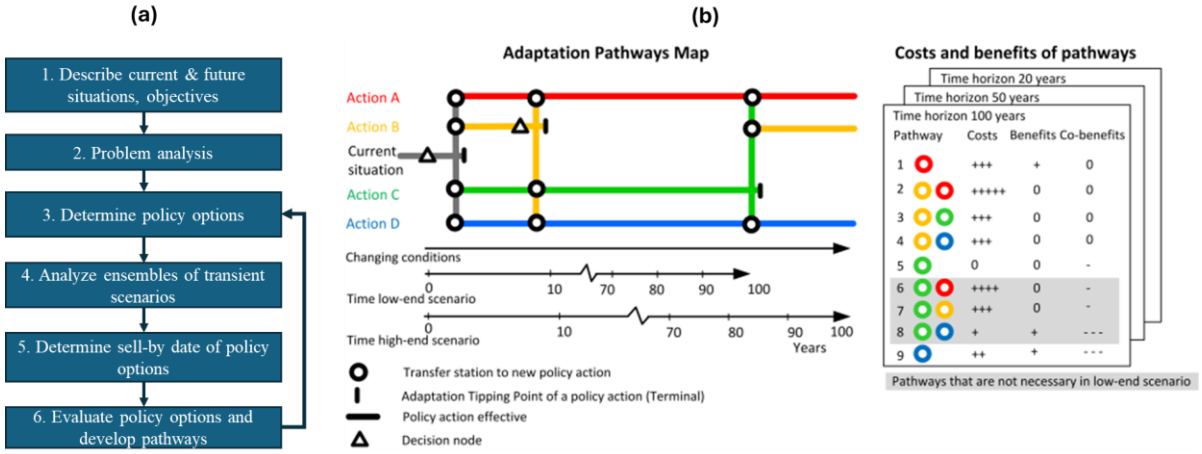

Figure 5-1. Steps involved in building the adaptation pathways map (a), and a schematic illustration of an adaptation pathways map (b), adapted from Haasnoot et al. (2013).

5.2.3 The role of systematic scenario development and energy-economy modeling

While the AP method has primarily been applied to climate change adaptation, particularly in flood management, it is often used in contexts where policies and actions can be quantitatively stress-tested under different scenarios. For example, a hydraulic model can help identify the sea-level rise threshold at which a specific flood protection measure, such as a dike, might fail, allowing decision-makers to determine tipping points across scenarios (Haasnoot et al., 2011, 2013). However, applying AP to novel technologies like DAC presents unique challenges. Policies and actions related to DAC might be more difficult to quantitatively stress-test due to their nature and they involve multiple, interacting dimensions of uncertainty (Motlaghzadeh et al., 2023). This subsection outlines the additional methods used to construct an adaptation pathways map for DAC in the Canadian context, specifically systematic qualitative scenario development and energy-economy modeling.

The objective of our decision problem is to enable the sustainable and equitable deployment of DAC at the scale required under different future conditions. Currently, DAC is an expensive technology, so overinvestment and commensurate stranded assets should be avoided. To understand the uncertainties influencing future DAC demand, a literature review and expert assessment were conducted to identify key uncertain system elements. These uncertainties were then categorized into ten groups spanning techno-economic and socio-regulatory dimensions, as described in Chapter 4. Given the interconnections among these elements—for example, the competitiveness of DAC may depend not only on its techno-economic characteristics but also on societal perceptions—a systematic scenario

development process was undertaken. The CIB method was used to engage stakeholder judgements from industry, government, academia, and NGOs in co-developing internally consistent scenarios, where the evolution of system elements reinforces one another.

Some of the ten system descriptors—such as the availability of low-carbon electricity, DAC cost, CO_2 storage potential, and national CDR demand—can be directly used to drive DAC deployment projections in IAM. Others, such as public acceptability and policy coherence, are more difficult or arbitrary to quantify in such models. GCAM, a community IAM developed by the Pacific Northwest National Laboratory (Joint Global Change Research Institute, 2023), is used to estimate DAC demand under a set of internally consistent scenarios derived from the scenarios developed using CIB (Weimer-Jehle, 2006) informed by DAC experts. In this study, we used a customized version of GCAM v5.4 developed by Fuhrman et al. (2023), which enables modeling a diverse range of CDR methods. In this version of the model, Canada is treated as a separate region, consistent with the structure of the standard global GCAM framework. More information about this model is provided in Chapter 3. This allowed us to explore a range of plausible DAC deployment pathways for the next 50 years (until 2075). In this approach, the two methods—CIB and the GCAM—play complementary roles. CIB facilitates the exploration of qualitative uncertainties and the development of internally consistent scenario narratives, while GCAM translates selected elements of these narratives into quantitative projections. Table 5-1 provides a comparison of the main features, applications, and integration potential of the two modelling approaches.

Table 5-1. Complementary methods for understanding climate and socio-technological systems: CIB and GCAM

Feature	Cross-Impact Balance (CIB)	Global Change Analysis Model (GCAM)
Type of Model	Qualitative scenario analysis tool	Quantitative integrated assessment model (IAM)
Developed By	Originally developed by Weimer-Jehle at the University of Stuttgart, Germany (Weimer-Jehle, 2006)	Pacific Northwest National Laboratory (PNNL), USA (Joint Global Change Research Institute, 2023)
Main Function	Identifies internally consistent socio-technical scenarios	Simulates global energy, economy, land, water and climate systems
Data Type	Categorical (qualitative and quantitative descriptors and their interactions)	Numerical (energy, emissions, land use, socio-economic indicators)
Core Methodology	Mathematical definition of internal consistency, based on ordinary differential equations (Weimer-Jehle, 2006)	Market equilibrium and systems modeling using differential equations
Primary Application	Exploratory scenario development under deep uncertainty	Policy analysis, emissions projections, understanding the role of new technologies for meeting specific climate targets
Output	Internally consistent qualitative scenarios (e.g., storylines, pathways)	Quantitative trajectories (e.g., emissions, carbon pricing, energy use, land cover)
Strengths	Captures non-quantifiable socio-political uncertainties; can be developed in a participatory fashion	Provides long-term numerical projections as a time series; used in major assessments, such as IPCC.
Limitations	Cannot project exact numerical outputs like emissions or costs. Time is represented episodically rather than sequentially.	Limited in incorporating or representing soft variables like public acceptability
Integration Potential	Ideal for guiding IAM input narratives (Kemp-Benedict, 2012; Schweizer, 2020) and framing uncertainties	Ideal for quantifying scenarios rooted in narratives or policy assumptions

5.3 Results

5.3.1 How qualitative scenarios inform quantitative modeling and adaptation pathways

Based on the systematic exploration of qualitative scenarios using the CIB method detailed in Chapter 4, 15 internally consistent futures were identified (Table 5-2), each representing a distinct future for the development of DAC technology in Canada. These scenarios vary across key dimensions, including

national CDR demand, DAC costs, public perception, policy coherence, availability of low-carbon electricity, and other critical factors.

In Table 5-2, each row represents a system descriptor, and each column corresponds to one of the 15 consistent scenarios. Descriptors are labeled with both a name and a corresponding letter (e.g., the first row represents "Competitiveness of DAC compared to other CDR methods," labeled as "H"). Most of the descriptors include three possible variants—H1, H2, and H3—representing low, moderate, and high levels, respectively. These variants are denoted by both color and a combination of letter and number (e.g., H1 for low competitiveness). To interpret a given scenario, read vertically down the column. For instance, Scenario 1 (S1) consists of the following variants: H1 (low competitiveness of DAC), I1 (low public perception), J1 (low policy coherence), D1 (low carbon pricing), E3 (high DAC cost), C1 (low availability of other DAC inputs), B1 (low pore space availability), G1 (low national CDR demand), F1 (low market demand for CO_2-based products), and A1 (low availability of low-carbon electricity). For analysis, the scenarios were grouped by DAC competitiveness: low (Scenarios 1–7), moderate (Scenarios 8–12), and high (Scenarios 13–15). This grouping helps reveal how other descriptor variants align with different levels of competitiveness. Starting from the second row, we identify descriptors with consistent patterns across competitiveness groups, highlighting co-occurring factors and points of divergence. For example, in all low-competitiveness scenarios (H1, Scenarios 1–7), public perception of DAC (descriptor I) is consistently low (I1).

The first application of the CIB method is to support more realistic quantitative modeling. Each plausible future implies a different level of DAC deployment, leading to distinct requirements for capital investment, electricity and heat inputs, and CO_2 transportation and storage infrastructure. Being prepared to meet these varying needs requires a strategic policy framework capable of supporting deployment at multiple scales. While quantitative models may identify certain scenarios as technically feasible—i.e., supply and demand equations are balanced or costs are minimized under constraints such as net-zero targets—these scenarios may still be implausible in the real world due to complex system interactions that such models are not equipped to capture. This is where the internally consistent scenarios generated by the CIB method become valuable: they can enhance the plausibility and relevance of quantitative scenario modeling by reflecting systemic interdependencies and qualitative dynamics. As illustrated in Section 5.3.2, GCAM-quantified scenarios that align with the CIB-derived narratives will capture a broad range of potential DAC deployment levels to construct the AP maps.

Table 5-2. Internally consistent scenarios of Canadian DAC landscape (Source: Chapter 4)

Descriptor	Scenarios														
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
H. Competitiveness of DAC relative to other CDR options	H1							H2					H3		
I. Public Perception of DAC	I1							I2							I3
J. Policy Coherence and Cooperation	J1								J2						J3
D. Carbon Pricing	D1		D2				D3	D1	D2		D3		D2		
E. Cost of DAC	E3				E2								E1		
C. Availability of Other DAC Inputs	C1				C2										
B. Usable Pore Space	B1						B2	B1	B2				B3		
G. National CDR Demand	G1		G2				G3	G1	G2		G3		G2	G3	
F. Market Demand for Products Utilizing Captured CO_2	F1				F3		F2	F1	F2					F3	
A. Supply of Low-Carbon Electricity Inputs	A1	A2		A3	A2	A3	A2			A3	A2	A3			

Legend
- Low
- Moderate/Medium/Partial
- High

The second application of the CIB method is to better understand the key uncertainties shaping the future of DAC and to use these insights to inform the design of AP maps. While not all descriptors of the DAC system—such as social acceptability or policy coherence—can be captured through quantitative modeling, they can play a crucial role in shaping adaptive strategies for DAC deployment. For instance, consider a scenario where DAC is highly competitive (H3) and national CDR demand is high (G2). In the CIB analysis, these conditions are reflected in Scenarios 14 and 15, where we consistently observe high availability of pore space (B3), sufficient access to DAC inputs like materials and heat (C2), and abundant low-carbon electricity (A2). This implies that for such a future to materialize, policies enabling these conditions must already be in place or actively implemented. Additionally, all highly competitive DAC scenarios are associated with low DAC costs (E1) and moderate carbon prices (D2). This highlights a key insight: DAC competitiveness cannot be achieved without significant cost reductions, and once those are in place, only moderate carbon pricing may be required to support the technology. Insights like these—derived from internally consistent CIB scenarios and summarized in Table 5-2—can help identify which enabling conditions and policy levers are necessary and should be explicitly addressed in AP maps. For example, Table 5-2 points to the importance of several key descriptors—such as pore space availability (B), low-carbon electricity (A), carbon pricing (D), and DAC costs (E)—in determining whether large-scale DAC deployment is viable.

To demonstrate an initial prototype of this novel decision-support methodology—integrating qualitative and quantitative scenarios with adaptation pathways—this study focuses on policy actions in three critical dimensions: (1) the economics of DAC, (2) electricity requirements for DAC and 3) CO_2 storage to cover the policies related to different descriptors of the CIB scenarios. Each of these dimensions may warrant a dedicated adaptation pathway map, embedding the most relevant policies to address uncertainty and to support adaptive planning.

5.3.2 Quantitative scenarios informed by CIB

The AP methodology offers a framework, along with visual tools, to aid in planning and decision-making under deep uncertainty. The primary objective of the final decision support tool (i.e., AP) is to guide decision-making across these dimensions by accounting for the full spectrum of possible DAC demand futures. From these, four representative scenarios—Very Low, Low, Moderate, and High DAC demand—are selected to capture the spectrum of possible futures. An even number of scenarios is intentionally chosen to discourage decision-makers from defaulting to a "middle" option as the most plausible. All four scenarios were internally consistent results from CIB and are treated as equally plausible, with no probabilities assigned to any of them. As noted, the aim is not to quantify every individual CIB narrative, but rather to capture a broad range of potential DAC deployment pathways aligned with the goal of reaching net-zero emissions by the target year (2050) and either sustaining that level through the end of the century or contributing to a net-negative emissions phase. The following section outlines the narrative behind each scenario, its connection to internally consistent storylines, and the approach used to quantify it using GCAM. Additional details on the modeling methodology are provided in Motlaghzadeh et al. (2025).

- **Very-Low DAC Demand (VD):** In this scenario, Canada achieves net-zero emissions by 2050 and maintains that status through the end of the century. The primary role of CDR is to offset residual emissions from hard-to-abate sectors which are those for which low-carbon alternatives are either unavailable or prohibitively expensive (Paltsev et al., 2021). These residual emissions are kept minimal through aggressive decarbonization, widespread adoption of low- or zero-carbon renewable energy, and societal shifts such as increased reliance on public transportation. Because residual emissions are so low, the overall demand for CDR is limited. Moreover, the need for technological CDR methods like DAC is especially constrained due to high associated costs and limited pore space for CO_2 storage, potentially due to public resistance to the technology. To model this scenario in

GCAM, we assumed a linear path to net-zero emissions, high DAC cost trajectories, robust growth in renewable energy, and socio-technological changes that reduce energy service demands and diminish the role of oil and gas. The model also incorporates land-use contributions as a carbon sink and limited availability of geological storage. This quantified scenario represents very low demand for DAC and is broadly consistent with CIB Scenario 2 (as shown in Table 5-2), which features moderate growth in low-carbon electricity (A2), a high-cost DAC trajectory (E3), low overall CDR demand (G1), very limited availability of pore space (B1) and DAC's low competitiveness to other CDR methods (H1). By default, GCAM assumes Canada has approximately 50 $GtCO_2$ of CO_2 storage capacity, distributed across several cost tiers (with lower-numbered grades being cheaper and prioritized first). To reflect the low availability of pore space in this scenario, total available storage is capped at 15 $GtCO_2$.

Figure 5-2a demonstrates the emissions and removals by sector for this scenario. As shown, DAC plays virtually no role in offsetting residual emissions in this scenario due to the overall low demand for CDR, driven by minimized residual emissions (113 $MtCO_2$ in 2050) and DAC's limited competitiveness compared to other removal options. In contrast, afforestation and reforestation contribute approximately 50 $MtCO_2$ in 2050, while bioenergy with carbon capture and storage (BECCS) accounts for around 60 $MtCO_2$ through electricity and hydrogen production. Although DAC is not deployed in this scenario, it is important to note that several ambitious mitigation efforts are underway in other sectors. These include deep decarbonization of transportation, which plays a key role in reducing residual emissions, and managing forests as carbon sinks, though the latter is becoming increasingly uncertain due to rising wildfire risks.

- **Low DAC Demand (LD):** As in the previous ("Very Low") scenario, total CDR demand remains low, as Canada reaches net-zero emissions by 2050 and maintains it through the end of the century with minimal residual emissions. However, this scenario differs from the Very Low DAC Demand scenario in two key ways. First, while the previous scenario assumed a high-cost DAC trajectory, this one adopts a moderate-cost pathway, enabling DAC to compete more effectively with other CDR options. Second, all CDR demand in this scenario must be met using non-conventional methods, as it assumes the forest sector does not contribute as a carbon sink. This quantified scenario aligns with Scenario 8 from the CIB study, which features a low availability of pore space (B1), moderate-cost DAC trajectory (E2), low CDR demand (G1), and moderate DAC competitiveness

(H2). Figure 5-2b illustrates sectoral emissions and removals for this scenario. DAC removes 28 $MtCO_2$ in 2050, increasing to 32 $MtCO_2$ by 2075.

- **Moderate DAC Demand (MD):** In this scenario, Canada not only achieves its net-zero target by 2050 but also contributes further to the 1.5°C global goal by reaching negative emissions after 2050. The scenario assumes that Canada takes action to repay its carbon debt—estimated at approximately 6.7 $GtCO_2$ starting in 2050—under the Per-Capita Convergence (PCC) burden-sharing principle. This repayment introduces an additional purpose for CDR beyond offsetting residual emissions. Available pore space is set at a moderate level, totaling 30 $GtCO_2$. Other scenario elements, such as DAC costs and its competitiveness relative to other CDR methods, mirror those in the Low DAC Demand scenario, where DAC remained viable among alternatives. As in the LD scenario, the forestry sector is assumed to have no carbon sink function. This quantified scenario reflects Scenarios 9 and 10 from the CIB study, which feature a moderate availability of pore space (B2), moderate-cost DAC trajectory (E2), moderate CDR demand (G2), and moderate DAC competitiveness (H2). In this scenario, DAC removes 20 $MtCO_2$ in 2050, rising to 120 $MtCO_2$ by 2075—primarily to meet equity-based obligations and to achieve the total level of negative emissions required by the model (as indicated by the dotted black line).

- **High DAC Demand (HD):** Similar to the Moderate DAC Demand scenario, Canada's contribution goes beyond merely achieving net-zero; however, in this case, it is based on the more ambitious Equal Per Capita (EPC) burden-sharing principle to help meet the global 1.5°C target. Under this ambitious equity framework, Canada is assigned a post-net-zero carbon debt of approximately 16.7 $GtCO_2$, resulting in a high national demand for CDR. To reflect the high pore space availability trajectory, no constraint is placed on total CO_2 storage capacity beyond GCAM's default assumption for the region (approximately 50 $GtCO_2$). In this scenario, DAC follows a low-cost trajectory and becomes highly competitive relative to other CDR methods. BECCS, a key alternative, faces constraints such as limited biomass availability. Similarly, other methods like enhanced weathering are restricted in their scalability. This quantified scenario reflects the potential DAC demand outlined in CIB Scenarios 14 and 15, which include a low-cost DAC trajectory (E1), high availability of pore space (B2), high CDR demand (G3), and high DAC competitiveness (H3). This

scenario primarily serves as an upper bound for DAC demand. As shown in Figure 5-2c, DAC deployment reaches approximately 87 $MtCO_2$ in 2050, rising to around 300 $MtCO_2$ by 2075.

As previously noted, DAC is an energy-intensive technology, and any decision-making process aimed at enabling its deployment must account for its energy requirements. In GCAM, three DAC variants are modeled: high-temperature DAC using natural gas for thermal energy (around 900°C), high-temperature DAC with electric heating, and low-temperature DAC. Figure 5-3b and Figure 5-3c show the electricity and natural gas needs under each DAC demand scenario. In the High DAC Demand scenario, DAC may require up to 1.6 EJ/year of natural gas by 2075—equivalent to 67% of Canada's total natural gas production—and approximately 0.45 EJ/year of electricity, or about 6% of total electricity generation. In comparison, the Moderate DAC Demand scenario would require 41% and 4% of national natural gas and electricity output, respectively, while the Low DAC Demand scenario would reduce these shares to 22% and 1.8%.

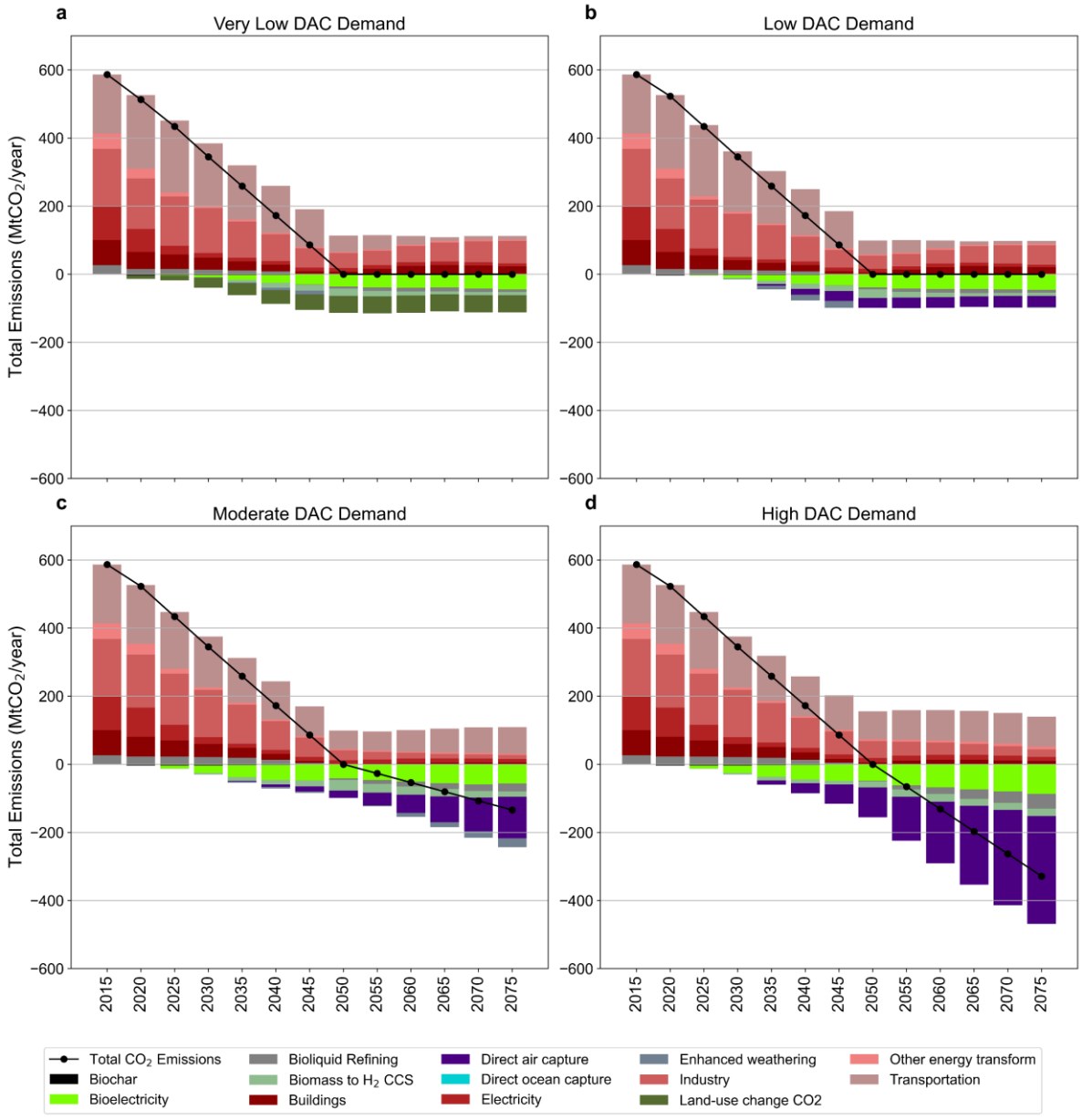

Figure 5-2. Emissions and removal by sector for different DAC demand scenarios: a) Very Low DAC Demand, b) Low DAC Demand, c) Moderate DAC Demand, d) High DAC Demand

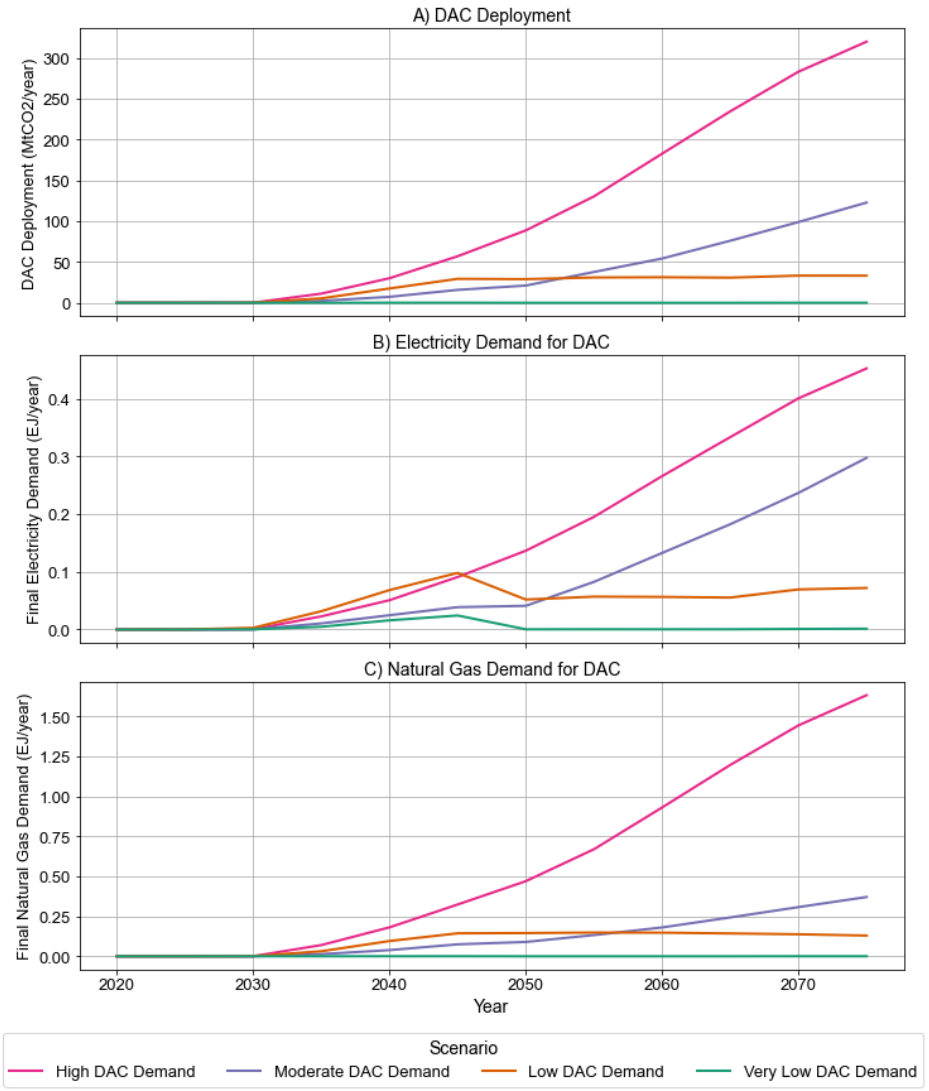

Figure 5-3. DAC demand and final energy requirements across scenarios: a) DAC deployment levels, b) Electricity demand for DAC, c) Natural gas consumption by DAC

5.3.3 Integrating qualitative scenarios, quantitative analysis, and policy reviews into adaptation pathways

Based on the results from our quantitative scenarios, future DAC demand trajectories vary widely, ranging from 0 to 300 $MtCO_2$/year by 2075, depending on socio-economic and technological conditions. In this section, we propose a targeted application of the AP method to support decision-

making across the above-mentioned dimensions of DAC deployment. These initial prototypes illustrate how the AP method can be used to navigate key uncertainties and will be further developed in collaboration with stakeholders, such as Canadian policymakers, in the next stages of the project. Additional dimensions—such as material supply—may also be explored through AP mapping, depending on stakeholder interest. For now, we focus on three of the most pressing and persistent challenges surrounding DAC: payment mechanisms and high costs, energy intensity and electricity supply, and CO_2 storage.

5.3.4 Describe the current and future situations and objectives (AP Step 1) and problem analysis (AP Step 2)

The overall objective of this decision-making process is to ensure that DAC can be deployed at the scales potentially required under different scenarios to help Canada meet its climate goals. This overarching aim translates into the three dimensions of DAC deployment that are of interest in this study.

The first decision problem centers on ensuring that appropriate policies or incentives are in place to cover the costs of DAC projects while providing a reasonable benefit margin for DAC developers. The second objective is to establish the necessary policies and infrastructure to supply electricity to DAC facilities at scales aligned with varying demand trajectories. The third objective is to ensure that infrastructure is in place to store the carbon captured by DAC at various deployment scales. As discussed in Section 5.3.2 and shown in Figure 5-3a, the scale of future DAC deployment in Canada may vary significantly depending on the scenario. At present, DAC activity in Canada remains at a very early stage, led by demonstration projects and start-up initiatives. The total annual CO_2 removal is still well below 1 $MtCO_2$/year. Current funding mechanisms include a mix of modest government incentives (e.g., investment tax credits), substantial philanthropic contributions (e.g., Breakthrough Energy, supported by Bill Gates), and purchases of carbon removal credits by corporate actors in the voluntary carbon market. However, the ability of these mechanisms to support large-scale deployment remains uncertain due to the substantial capital investment that may be required. Therefore, an AP map focusing on the economics dimension should explicitly address this financial challenge.

Regarding the electricity supply dimension, the modest scale of current projects allows DAC companies to either draw electricity from the grid (e.g., Carbon Engineering's Squamish pilot) or secure clean electricity through power purchase agreements (e.g., Deep Sky's project in Innisfail). While these

approaches are currently feasible, scaling up DAC could introduce new challenges and risks. For example, relying on grid-supplied electricity at large scales could shift costs and burdens onto local communities. An AP map for this dimension should therefore anticipate and address such risks, ensuring electricity needs can be met equitably and sustainably at larger scales.

Finally, with respect to storage, most current DAC projects in Canada—as of July 2025—remain at the pilot or early demonstration stage, with deployment levels measured in tens to thousands of tonnes per year. For instance, Carbon Engineering's pilot plant in Squamish, British Columbia, built in 2015, captures approximately 365 tCO_2/year and does not store the CO_2; instead, it uses it to produce synthetic fuels. Carbon Engineering is also developing a much larger "Air to Fuel" facility in Merritt, BC, anticipated to become operational in 2026, with a projected capacity of 250,000 tCO_2/year. This facility will likewise utilize the captured CO_2 for synthetic fuel production, not permanent storage (Government of British Columbia, 2021). In contrast, Deep Sky's new DAC test centre in Innisfail, Alberta, operational since mid-2025, integrates multiple DAC technologies and captures approximately 3,000 tCO_2/year, all of which is transported for permanent geological storage in a deep saline aquifer (Semmens, 2025). Other projects under development in Quebec—including initiatives by Deep Sky and Skyrenu—aim to scale up DAC with permanent storage, either through injection into geological formations or by accelerating mineralization reactions using mine tailings. At this early stage, some projects continue to focus on CO_2 utilization, which can offer near-term revenue, but there is a clear shift toward permanent storage as utilization markets remain limited and concerns about carbon accounting persist. While large-scale CO_2 storage from DAC has not yet occurred in Canada, the country has significant experience with storing CO_2 from point-source emissions, and several geological storage sites—especially in Alberta, Saskatchewan, and parts of Quebec—are operational or being actively developed to support future carbon storage projects (Canada Energy Regulator, 2025). In terms of regulation, subsurface resources in Canada are owned by the provinces. Alberta, Saskatchewan, and British Columbia have established regulatory frameworks to enable safe and permanent geological CO_2 storage while other provinces still lack such regulations according to Canada's 2023 carbon management strategy report (Natural Resources Canada, 2023).

5.3.5 Determine policy options (AP Step 3)

Having clarified the current situation and the objectives of the decision-making problem, the next step is to compile a list of potential policies, actions, or frameworks that could help achieve these objectives

(e.g., providing financial support for DAC). Some of these measures may already have been considered or discussed by the Government of Canada, while others may emerge from research-based policy proposals. The latter is particularly important, since some policies originally designed for other purposes (e.g., low-carbon fuel standards) have implications for DAC, the technology itself remains novel, and the policy ideas are rapidly changing, with many policies yet to be fully established. To compile a list of potential policies and frameworks across different dimensions of decision-making for DAC, we drew on several complementary methods and sources: (1) a "deep search" using a large language model (ChatGPT-4) to identify policy actions discussed in publicly accessible documents, (2) insights from Cortinovis et al. (Cortinovis et al., 2024) which reviewed DAC-relevant policies in Canada, and (3) internal vetting with the Waterloo Climate Intervention Strategies Lab (Waterloo Climate Intervention Strategies Lab, 2025).

Table 5-3 presents seven preliminary economic policy instruments or frameworks that the Government of Canada might consider supporting the deployment of DAC. These policies include carbon pricing (via taxes and emissions trading systems), investment and production tax credits (ITC and PTC), contracts for difference (CfD) and advance market commitments, public procurement of carbon removal, government grants and loan guarantees, carbon removal obligations or take-back mandates, and carbon offset credits within compliance and voluntary markets. Canada has already implemented some of these instruments—most notably carbon pricing and investment tax credits—while others, such as carbon removal obligations and take-back mandates, remain at the proposal stage and have primarily been discussed in academic and policy forums. Importantly, the intensity and design of some of these policies can vary significantly. For instance, carbon pricing policies can follow different trajectories with varying implications for DAC viability. In this analysis, we consider the three illustrative carbon pricing pathways from the CIB study: (1) a *low* pricing scenario, where the carbon tax increases by no more than \$10/tCO_2 annually until 2050, followed by a \$5/tCO_2 annual increase until 2075; (2) a *medium* pricing scenario, reflecting Canada's current policy trajectory, where the tax increases by \$10–30/tCO_2 annually to 2050, then by \$15/tCO_2 per year through 2075; and (3) a *high* pricing scenario, where the carbon tax rises by \$30/tCO_2 per year until 2050, followed by a \$15/tCO_2 annual increase thereafter.

Table 5-3 also outlines six key electricity supply and infrastructure policies or frameworks related to DAC that might be implemented in Canada. These policies range from spatial strategies, such as DAC hubs that co-locate clean power and CO_2 storage infrastructure, to system-wide planning

measures like integrating DAC demand into long-term energy planning. While some elements—such as clean energy siting policies and power purchase agreements (PPAs)—have seen partial implementation in provinces like Alberta and Ontario, most policies remain at early stages of development and lack DAC-specific design. Notably, there are policy gaps in incorporating DAC into integrated resource plans and in dedicating clean energy build-outs exclusively for DAC applications. Transmission and distribution system upgrades, though underway in broader federal-provincial initiatives (e.g., Atlantic Loop), have yet to explicitly consider DAC-related needs. While DAC will have significant energy implications at high deployment levels, Canada has a diverse portfolio of low-carbon energy resources — including hydropower, nuclear, wind, solar, and emerging renewable options — that could be strategically mobilized with proactive and coherent planning (Council of Canadian Academies, 2015). Finally, Table 5-3 presents five actions or frameworks related to CO_2 sequestration, primarily focusing on the storage medium (offshore, onshore, or hybrid models), as well as distributed versus hub-based deployment models which has implications for the CO_2 transportation infrastructures that might be needed. Table 5-3 also includes a policy package—Exploration, Regulation, Expansion, and Utilization (EREU) of Pore Space—which outlines the phased steps required to enable CO_2 storage implementation.

Due to the interconnected nature of the challenge, meeting DAC demand across different dimensions will likely require a coordinated suite of complementary policies and frameworks. For example, carbon pricing may need to be implemented in conjunction with Contracts for Differences (CfDs) to build market confidence in DAC deployment through guaranteeing a fixed price per tonne of CO_2 removed in future (Beugin, 2023). To reflect such interdependencies, certain policies have been bundled into packages for representation on the AP maps. In the subsequent stages of the AP methodology, the "sell-by dates" of these policy packages will be evaluated, and adaptive pathways—sequences or combinations of packages tailored to varying levels of DAC demand across the economic and electricity dimensions—will be constructed. To enhance the credibility and realism of the compiled policies, future phases of the project will involve sharing this portfolio with Canadian decision-makers to gather feedback, refine the content, and validate both the policy measures and the underlying assumptions about their timing and effectiveness.

Table 5-3. Economic and Electricity Supply Measures and Frameworks for Direct Air Capture Deployment

Policy or Framework Name	Dimension	Description	Implementation Status
Carbon Pricing (Taxes and Emissions Trading Systems)	**Economics**	This policy category places an explicit price on CO_2 emissions—either through a carbon tax or a cap-and-trade system—creating a market incentive for emissions reductions or removals. A sufficiently high carbon price can make DAC economically viable by allowing operators to sell credits or avoid carbon fees. Trading systems (e.g., cap-and-trade) can incorporate negative emissions by letting DAC credits offset positive emissions.	Canada's federal carbon price is set at C$95 per tonne in 2025 and will rise to C$170 by 2030 (Department of Finance Canada, 2025). Large industrial emitters operate under an output-based pricing system or OPBS (Government of Canada, 2021), which allows them to either pay the carbon price or use eligible credits for compliance. Canada is also developing a federal greenhouse gas offset system, including a draft protocol for DAC with geological storage (Government of Canada, 2025). Once finalized, this would enable DAC projects to generate compliance credits under the output-based pricing system.
Investment Tax Credits (ITC) & Production Tax Credits (PTC)	**Economics**	Tax credits help reduce project costs by either subsidizing capital investments through Investment Tax Credits (ITCs) or providing per-tonne payments for CO_2 removal via Production Tax Credits (PTCs). These incentives directly improve project economics—ITCs lower upfront costs, while PTCs offer ongoing revenue for each tonne of CO_2 captured (Hickey et al., 2023).	Canada introduced a refundable CCUS Investment Tax Credit in Budget 2022, offering up to a 60% credit on DAC equipment, 50% on other capture equipment, and 37.5% on storage or transport, for expenditures from 2022–2030 Canada Revenue Agency, 2024). This federal ITC is active, and Alberta has proposed a 12% provincial grant on CCUS capital (Government of Alberta, 2025). Canada has not yet introduced a production tax credit for CO_2 removal, unlike the U.S., where such incentives support DAC hubs.
Contracts for Difference (CfD) and Advance Market Commitments	**Economics**	Contracts for difference (CfDs) offer price certainty by guaranteeing a fixed price per tonne of CO_2 removed. Under a typical arrangement, the government or another funder agrees to cover the gap between an agreed "strike price" (such as the cost of removal) and the market price for CO_2 credits. If the market price is lower, the funder pays the difference; if it's higher, the project returns the surplus. This mechanism helps de-risk investment by ensuring a minimum level of revenue per tonne (Beugin, 2023).	As of 2025, Canada has not implemented a CfD or AMC at the federal level. These tools have been discussed in policy circles (Chen, 2025) as a way to guarantee a stable price for carbon removal in the absence of a mature market. Companies like Microsoft, Shopify, and the Frontier AMC consortium act as quasipublic buyers, funding removals through advance commitments.

Policy or Framework Name	Dimension	Description	Implementation Status
		Advance Market Commitments (AMCs) operate on a similar principle, pledging to purchase a specific volume of CO_2 removals at a set price in the future (Trendafilova, 2024). This signals reliable demand and gives developers confidence to invest (Ransohoff, 2024). Both CfDs and AMCs are demand-pull instruments—they commit future payments for carbon removal outcomes and stimulate near-term investment.	
Public Procurement of Carbon Removal	**Economics**	Government procurement allows public agencies to directly purchase carbon removal as a service or credit. This can take the form of contracts for a specified volume of CO_2 removed and stored, effectively making the government an assured buyer in the market (Meckling & Biber, 2021). Procurement is a powerful tool to create early demand—just as it has been for other innovations like vaccines or clean energy.	In 2025, the federal government launched an initiative to purchase CO_2 removal from industry, starting with a $10 million commitment through 2030. The goal is to stimulate early market demand by positioning the government as a buyer of verified removals, helping to advance progress toward national net-zero targets (Treasury Board of Canada Secretariat, 2024).
Government Grants and Loan Guarantees	**Economics**	This category includes grants, low-interest loans, and loan guarantees to support DAC projects. Grants offset capital or R&D costs, while loans guarantee lower borrowing risks and costs.	The Canada Infrastructure Bank and Export Development Canada have mandates to support clean technologies and have already financed CO_2 transport infrastructure (Natural Resources Canada, 2023), positioning them to potentially support future DAC projects.
Carbon Removal Obligations and Take-Back Mandates	**Economics**	Carbon Removal Obligations (CROs) or Carbon Take-Back Obligations (CTBOs) are regulatory mandates requiring certain sectors—such as fossil fuel producers—to permanently remove and store a portion of carbon from the atmosphere. Companies can either conduct the carbon removal themselves or pay certified providers (e.g., DAC operators) to do it on their behalf (Allen et al., 2022; Jenkins et al., 2021). The scale of the obligation may vary over time. Some propose that during the path to net-zero, companies should	These policies are largely conceptual or in the proposal stage but may become essential later in the century as Canada—and the world—enters a period of negative emissions required to reverse temperature overshoot.

Policy or Framework Name	Dimension	Description	Implementation Status
		begin by compensating a small fraction of their emissions with permanent CDR, gradually increasing the requirement as emissions decline. This staged approach would help channel financial resources into the emerging CDR sector (Hickey et al., 2023; Honegger et al., 2021). Others suggest a carbon debt approach: if companies exceed annual emission caps, the excess should be tracked as a debt and repaid through CDR, potentially with an interest rate. This mechanism would incentivize compliance and ensure that overshoot is compensated with high-integrity removals (Bednar et al., 2021, 2023. Eventually, in the net-negative emissions phase, national CDR needs will exceed residual emissions. At that stage, CROs or CTBOs could be used to mandate removals from corporations or sectors with higher historical responsibility for emissions (those who are responsible for the carbon budget overshoot). This would resemble the burden-sharing frameworks already applied at the international level (Gidden et al., 2023) or some subnational (Kuriakose et al., 2022).	
Carbon Offset Credits (Compliance and Voluntary Markets)	**Economics**	Offset credits represent one tonne of CO_2 reduced or removed and can be sold to compensate for emissions elsewhere. DAC projects that capture and store atmospheric CO_2 can generate removal credits, which may be sold in compliance markets (to meet regulatory obligations) or voluntary markets (to meet self-imposed climate goals).	In January 2025, the federal government released a draft DAC offset protocol for geological storage. Once finalized, it will enable DAC projects to generate federal credits under the Greenhouse Gas Offset Credit System for use by regulated emitters in the OBPS. No credits have been issued yet, as projects remain in development (Government of Canada, 2025). Interest in voluntary Canadian DAC credits is growing, but robust standards and MRV systems are still needed (Trencher et al., 2024). The federal protocol may help establish these foundations.

Policy or Framework Name	Dimension	Description	Implementation Status
DAC Hubs	**Electricity**	Designated geographic clusters with co-located clean electricity sources, CO_2 storage infrastructure, and transport systems. Reduces need for extensive grid build-out by concentrating demand and leveraging shared assets.	Emerging concept – piloted in U.S. DOE hubs (U.S. Department of Energy, Office of Clean Energy Demonstrations, 2025)
Clean Energy Siting Policies	**Electricity**	Streamlined permitting, zoning, and land-use frameworks for building renewable energy and storage near DAC locations. Includes policies prioritizing use of degraded land, agrivoltaics, or brownfield redevelopment.	Partially implemented in Alberta & Ontario; evolving.
Power Purchase Agreements (PPAs)	**Electricity**	Long-term electricity contracts between DAC developers and electricity generator, enabling dedicated energy supply. PPAs are usually signed for a duration of 5 to 20 years, with the energy buyer (here DAC company) committing to purchase electricity at a predetermined price throughout the contract term.	Widely used in Alberta and emerging in other provinces; DAC-specific applications are not yet formalized.
Integration of DAC Demand in Energy Planning	**Electricity**	Incorporating projected DAC electricity demand into provincial and federal Integrated Resource Plans and load forecasts. Supports anticipatory grid investment and generation planning.	Not currently included; policy gap. Potential for integration via provincial utilities.
Dedicated Clean Energy Build-Out	**Electricity**	Policy frameworks and financing tools to develop new clean energy generation (e.g., solar and wind) specifically allocated for DAC. Could involve government-led tenders or developer-led builds backed by carbon removal contracts.	Enabled indirectly by clean power funding; no specific linkage to DAC yet.
Grid Expansion	**Electricity**	Transmission and distribution infrastructure enhancements to connect distributed DAC units to clean power sources. Includes interprovincial interties, microgrids, and flexible load integration to balance variable supply and DAC load.	Proposal for Atlantic Loop (Public Policy Forum, 2023). Transmission planning timelines remain lengthy (~10-20 years).

Policy or Framework Name	Dimension	Description	Implementation Status
Onshore Storage	**CO_2 Storage**	There are four main types of onshore storage formations, each with different characteristics such as injection costs, technical complexity, and storage capacity: • Deep saline aquifers – Porous rock formations located beneath an impermeable cap rock that prevents CO_2 leakage. • Mature oil fields – Large-producing oil fields (e.g., in Western Canada) can be used for CO_2 injection to enhance oil recovery. However, the overall storage potential is limited. • Depleted oil and natural gas reservoirs – These formations are already proven to hold hydrocarbons and can now be repurposed for CO_2 storage. • Basalt formations – Reactive igneous rocks that can mineralize CO_2, turning it into solid carbonates over time.	Canada has been implementing CCS from point-source emissions since 1982, primarily using the captured CO_2 for enhanced oil recovery by injecting it into mature oil fields. The country also possesses significant potential for CO_2 storage in deep saline aquifers, particularly across western provinces. Estimates suggest that Saskatchewan, Alberta, and Manitoba have theoretical storage capacities of approximately 290, 79, and 13.5 $GtCO_2$, respectively. Preliminary assessments have also identified potential storage capacities in Quebec and British Columbia, estimated at 2.8–3.2 and 3-4.2 $GtCO_2$, though these figures remain uncertain (Felder et al., 2024).
Hybrid Model (Both Offshore and Onshore)	**CO_2 Storage**	In addition to onshore storage alternatives, offshore options also exist: • Deep ocean injection – CO_2 can be injected into deep ocean waters (depths greater than 1,000–1,500 meters), where it dissolves or forms a stable layer near the seafloor. • Mineralization on the seafloor (geochemical storage) – CO_2 is injected into basaltic formations beneath the ocean floor, where it reacts with minerals to form solid carbonates, effectively storing it permanently.	Canada, with its vast coastline along the Atlantic and Pacific Oceans, has yet to pursue offshore CO_2 injection but holds considerable potential for offshore storage. In British Columbia, subseafloor basalt formations offer mineralization potential for storing up to 50 million metric tons of CO_2. The Atlantic provinces, particularly the Scotian Shelf, Newfoundland Shelf, Gulf of St. Lawrence, and Bay of Fundy, contain sedimentary formations, salt domes, and depleted gas fields with an estimated capacity of up to 660 $GtCO_2$. In the Arctic, the Mackenzie-Beaufort area features gas hydrates within porous sandstone and limestone, presenting a promising but less explored CO_2 storage option (Zendehboudi et al., 2025).

Policy or Framework Name	Dimension	Description	Implementation Status
Distributed DAC Model	**CO_2 Storage**	In this setting, multiple DAC plants are located across the country, each transporting captured CO_2 to nearby storage sites. In contrast with a hub-based model, this approach requires the expansion of CO_2 pipeline infrastructure or other mode of transportation at the regional level. This model would allow prioritizing one of the key inputs to the DAC system—either clean energy or storage—while meeting the other system's demand through transportation of either energy or captured carbon. Such an approach could also generate additional socio-economic benefits for a broader range of communities.	Not implemented yet.
Hub-based Model	**CO_2 Storage**	In this setting, a limited number of centralized DAC hubs are co-located with suitable storage sites. CO_2 is transported via local pipelines—or by ship in the case of offshore storage—over relatively short distances to the designated storage facilities.	Not implemented yet.
Exploration, Regulation, Expansion, and Utilization (EREU) of Pore Space	**CO_2 Storage**	Other policy actions that involve identifying and assessing suitable geological formations (explore), establishing clear legal and regulatory frameworks (regulate), increasing access to and capacity of storage sites (expand), and operationalizing them for long-term CO_2 injection and storage (use). I will call such policy actions Explore, Regulate, Expand, and Use (EREU). This approach ensures safe, scalable, and accountable deployment of carbon storage infrastructure.	This suite of policies is primarily aimed at enabling CO_2 storage by supporting key steps in the development and operation of storage sites. Some provinces are already implementing similar strategies on a smaller scale to support CCS projects.

5.3.6 Analyze ensembles of scenarios (AP Step 4)

Within the AP methodology, scenarios are used to stress-test policy packages against the objective function. In this study, scenarios correspond to the quantified DAC demand trajectories and other relevant system inputs (as illustrated in Figure 5-3). The aim is to assess whether the proposed sequences of policy packages (Table 5-4) are capable of effectively supporting these scenarios under a range of possible conditions.

5.3.7 Determine the sell-by-date of policy options or packages (AP Step 5)

As noted earlier, the primary aim of this chapter is to propose a methodological approach that integrates insights from multiple decision-making tools—particularly scenario analysis (both qualitative and quantitative) and adaptation pathways mapping. The examples provided are illustrative and may evolve in later stages of the ongoing project. Determining the *sell-by-date* of policy options for DAC is more complex than in typical applications of the AP, which often involve clearly defined physical systems and models. For instance, in sea-level rise adaptation, engineers can assess whether infrastructure options (e.g., dikes, embankments, or dams) will remain effective under different sea-level scenarios using hydraulic models. In contrast, DAC-related policies—such as carbon pricing—lack hard physical constraints and are influenced by social, economic, and political factors. For example, while carbon pricing may technically support any level of DAC deployment, high levels (e.g., hundreds of $MtCO_2$/year) could face resistance due to perceived financial burdens if the capital or operating costs of DAC remain too high, leading to social or political infeasibility. The underlying rationale and estimated sell-by-dates for policies and frameworks related to the economic dimension are presented in Table 5-4. The electricity supply and storage dimensions will be discussed in Section 5.3.8, together with the adaptation pathways maps.

Table 5-4. Policy packages for the economic dimension and the rationale behind their effectiveness and sell-by-dates

Package	Dimension	Policy Mix	Effectiveness of the Package
ECON1	**Economics**	Waste Management Model (though carbon pricing or PTCs)	While carbon pricing sends an important market signal, it is insufficient on its own to drive early-stage DAC deployment due to high upfront costs. In the near term, carbon pricing must be complemented by mandates, subsidies, or long-term contracts to create viable market conditions. As DAC costs decline through learning-by-doing and economies of scale—and as climate targets tighten—carbon pricing becomes more effective. Pricing can take the form of a carbon tax or an emissions trading system that incorporates DAC credits. Alternatively, a production tax credit (PTC) model can be used. ECON1 package is best suited for the later stages of DAC deployment—above 100 $MtCO_2$/year, when DAC also contributes to negative emissions—as costs decline and the government adopts a public service role in atmospheric CO_2 removal, supporting fair contributions toward the Paris Agreement's 1.5°C target.
ECON2	**Economics**	High Carbon Price or PTCs + CfDs + Compliance Market	In the early stages of DAC deployment—when costs remain high—a carbon price would need to be extremely high to be effective, which introduces socio-political challenges. As an alternative, high production tax credits (PTCs) can be targeted specifically at DAC to avoid conflating them with carbon taxes aimed at broader decarbonization. Given the immature market for DAC, contracts for difference (CfDs) may also be needed to provide sufficient market certainty for DAC project developers. This policy package is most suitable for deployment levels up to 100 $MtCO_2$/year—an approximate threshold representing moderate-scale deployment before DAC shifts toward generating net negative emissions.
Current Situation	**Economics**	A moderate carbon pricing trajectory, government procurement of CDR, investment tax credits, and voluntary carbon markets.	All current policies and incentives supporting DAC in Canada are limited in scale, and we estimate that, collectively, they are unlikely to support more than 5 $MtCO_2$/year of deployment. The prevailing carbon price—approximately CAD 95 per tonne—is far below the current cost of DAC, which ranges in the hundreds of dollars per tonne. The federal government has allocated $10 million for carbon removal procurement; even if fully dedicated to DAC at an assumed cost of CAD 400 per tonne, this would only support about 25,000 tonnes of CO_2 removal. Additionally, the voluntary carbon market remains constrained in both size and credibility. Overall, we consider 5 $MtCO_2$/year a generous upper-bound estimate for what current policies can realistically enable.
ECON3	**Economics**	Modest CDR Mandates (% Emissions) + Non-CDR CO_2 Pricing (e.g. OBPS)	An alternative to treating sequestered and emitted carbon equally (i.e., ECON2, which includes DAC credits in compliance markets) is to directly mandate industries or sectors to remove a fixed percentage of their emissions through CDR or DAC. A carbon pricing mechanism could still operate in parallel to support broader decarbonization. These policies remain effective as long as residual emissions persist. However, when the total CDR requirement exceeds residual emissions (our models indicate this occurs beyond 100 $MtCO_2$)—for instance, if Canada seeks to repay its carbon debt—an additional economic policy would be necessary (e.g., ECON4)

Package	Dimension	Policy Mix	Effectiveness of the Package
ECON4	**Economics**	CDR Take-Back (% historical) + Non-CDR CO_2 Pricing (e.g., OBPS)	A more advanced version of ECON3 suited for the post-net-zero context is ECON4, in which the Government of Canada mandates historical emitters to remove a portion of their past emissions using permanent CDR methods such as DAC. This policy is best applied in the later stages of deployment—assumed here to be above 100 $MtCO_2$/year—when DAC is primarily used for net-negative emissions. A carbon pricing mechanism can still operate in parallel to support ongoing decarbonization efforts.

5.3.8 Evaluate policy options and develop pathways (AP Step 6)

Economics of DAC

Figure 5-4 presents the prototype of the AP map for the economic dimension of future DAC deployment in Canada. At the bottom, an axis labeled "DAC deployment ($MtCO_2$/year)" shows the full range of deployment levels, from zero to the maximum observed in our scenarios—340 $MtCO_2$/year, which occurs in the High DAC Demand scenario. Beneath this axis are four scenario-specific timelines, each corresponding to one of the DAC scenarios. These timelines indicate when different levels of DAC deployment, as shown in Figure 5-4-a, are expected to be reached under each scenario. For example, in the Very Low DAC Demand scenario, deployment never exceeds 1 $MtCO_2$/year. In the Low scenario, it gradually increases to approximately 42 $MtCO_2$/year by 2080. In contrast, the High DAC Demand scenario reaches its peak deployment level of 340 $MtCO_2$/year around 2080. These variations represent the uncertainty dimension that policy strategies must account for.

Above the deployment axis are colored lines representing individual policies or policy packages. Each line's color matches the policy name and indicates the applicable range of DAC deployment for which the policy remains effective. For example, the current policy environment (silver line) is only suitable for up to ~5 $MtCO_2$/year. Beyond that, a transition is necessary. This transition is represented by branching lines leading to two alternative policy packages of ECON2 and ECON3. As demand for higher deployment levels increase further, another transition may be needed. This leads to two additional packages: ECON 1 and ECON4.

This pathway map illustrates how different policy packages can be introduced, maintained, or phased out based on the scale of DAC deployment required to meet demand and uncertainties in future demand. Having explained how to interpret the map, we now turn to the narrative it presents. Below the deployment axis are four time horizons depicting possible "changing conditions", which illustrate the varying timelines in which different levels of DAC deployment may occur in Canada. Some deployment levels may not materialize under certain scenarios—for instance, in a very low DAC demand trajectory, deployment remains below 1 $MtCO_2$/year. In this very low-demand case, Canada's current policy setting—characterized by moderate carbon pricing, investment tax credits for DAC projects, and voluntary purchases of CDR credits—could remain sufficient for limited deployment, up to around 5 $MtCO_2$/year. However, in scenarios with low to moderate DAC demand, the current policy mix becomes inadequate. This inadequacy stems from the fact that DAC remains relatively expensive; current carbon prices alone are insufficient to make it a competitive CDR option to alternative approaches such as BECCS. Moreover, both voluntary carbon markets and the Canadian government's procurement of CDR have limited capacity. Before reaching this decision point, policymakers would

need to consider adopting more robust instruments—such as those in the ECON2 and ECON3 policy packages.

Figure 5-4 illustrates two key policy options beyond this threshold. ECON2 includes high carbon prices or production tax credits (PTCs), which offer payments (e.g., 300-500 dollars per tCO_2) to DAC operators that exceed the current cost of DAC. In ECON2 pathway, it is critical that DAC is eligible in compliance offset markets, allowing credits to count toward emissions reductions. However, this approach carries risks and requires strong monitoring, reporting, and verification (MRV) systems to ensure the integrity of decarbonization efforts (Bednar et al., 2023). Given the uncertainties and potential breakthroughs in DAC costs, Canada could also adopt CfDs to guarantee a minimum price for DAC credits—providing operators with financial certainty and encouraging investment.

While ECON2 addresses decarbonization and CDR deployment within a single market framework, ECON3 adopts a different strategy. In this policy strategy, carbon pricing remains focused solely on emissions reductions, and DAC credits are not eligible in compliance markets. Instead, the government may introduce CDR or DAC mandates requiring certain sectors or companies to compensate for a portion of their emissions—particularly the residual emissions that are hardest to abate. These mandates would be designed to avoid over-reliance on CDR. For example, if Company X currently emits 10 $MtCO_2$ annually and anticipates needing CDR for 1 $MtCO_2$ (10%) of residual emissions in a decade, it could begin deploying CDR gradually, starting now.

All scenarios assume that Canada reaches net-zero emissions by 2050. Under such conditions, DAC deployment might still exceed 100 $MtCO_2$/year if DAC deployment in Canada is no longer limited to offsetting residual emissions—it would begin contributing to a broader net-negative emissions target. At this scale, the demand for carbon dioxide removal exceeds residual emissions, and additional policies or packages must be introduced. Two key policy options at this stage are ECON1 and ECON4, each reflecting a distinct approach to managing the economics of the negative emissions period.

In ECON1 (waste management model), a low to moderate carbon price is maintained. This price serves a dual purpose: (1) incentivizing continued emissions reductions and compensating for remaining residual emissions, and (2) providing partial funding for DAC projects. However, revenue generated through carbon pricing is unlikely to fully cover the high costs of DAC at scale. As such, this model resembles a public waste management approach, in which the Government of Canada funds atmospheric clean-up—removing historical emissions—through general public revenue rather than direct polluter payments.

An alternative is ECON4, which introduces carbon take-back mandates for provinces, sectors, or corporations with high historical responsibility for Canada's CO_2 budget overshoot. Under this framework, these entities are obligated to remove more CO_2 than they emit—moving beyond compensation for residual emissions. While some level of CO_2 pricing remains in place to keep current emissions near zero, these mandates ensure that historical emitters take greater responsibility for achieving net-negative outcomes.

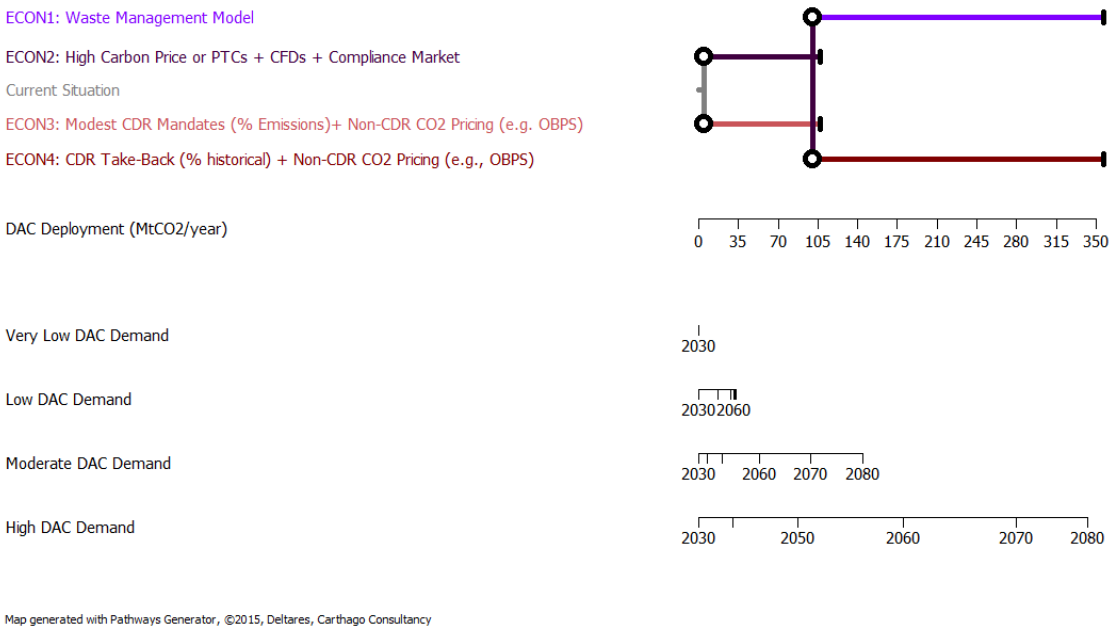

Figure 5-4. An adaptation pathways prototype for the economic aspects of direct air capture deployment in Canada

Energy Supply of DAC

Figure 5-5 illustrates a high-level AP map for the electricity supply dimension of DAC deployment. The structure of this map closely mirrors that of Figure 5-4. As with the economic dimension, electricity demand is not expected to pose a significant challenge at low levels of DAC deployment—specifically, below 5 $MtCO_2$/year. However, beyond this threshold, a decision point is reached at which policymakers must proactively address the long-term electricity supply for DAC systems. This threshold is never encountered under the very low DAC demand scenario but arises between 2034 and 2040 in the other three scenarios.

Beyond this terminal point, several policy pathways become relevant, notably ELEC2, ELEC3, and ELEC4:

- ELEC2 entails prioritizing DAC deployment in regions with low-carbon electricity grids (such as Quebec, British Columbia and Ontario (Environment and Climate Change Canada, 2024), supported by PPAs to secure future electricity supply and integrate DAC into energy system planning.
- ELEC3, by contrast, does not require clean electricity use. Instead, DAC can operate wherever existing grids can supply the needed electricity, regardless of carbon intensity.
- While ELEC2 and ELEC3 leverage existing grid capacity, ELEC4 envisions a strategy where DAC operators are required to develop their own clean electricity sources, potentially with future grid connection to share surplus electricity.

At even higher levels of DAC deployment—with correspondingly higher electricity requirements—two structurally distinct strategies emerge: ELEC1 and ELEC5. In the illustrative moderate or high DAC demand scenarios, these strategies may be required around the net-zero year (early 2050s) or soon after (2070).

- ELEC1 represents a hub-based approach, where a limited number of large-scale DAC hubs (each potentially capturing tens of megatons of CO_2 per year) are sited in strategic locations with co-located access to low-carbon electricity, CO_2 transport infrastructure, and geological storage.
- ELEC5, alternatively, assumes a distributed deployment model with numerous smaller DAC facilities across the country. However, this strategy poses considerable logistical challenges due to the unlikely co-location of clean energy resources, storage sites, and skilled workforce at the required scale. As such, it is likely to require significant expansion of the national electricity grid, enabling power transmission from provinces with abundant low-carbon electricity—but limited CO_2 storage capacity—to areas better suited for sequestration.

CO_2 Storage

Figure 5-6 presents a prototype AP map for CO_2 storage. Similar to Figure 5-4 and Figure 5-5, the X-axis represents changing conditions—here, DAC demand under different scenarios—while the Y-axis displays eight storage-related policy packages (STORE1 to STORE8). These packages represent high-level strategies for how CO_2 captured from DAC might be stored, rather than specific regulatory instruments like pore space legislation. Two key distinctions define these approaches: (1) the

geographic scope of storage—either onshore (STORE5 to STORE8) or a combination of onshore and offshore (STORE1 to STORE4); and (2) the infrastructure model—either a distributed approach requiring extensive CO_2 transportation infrastructure (e.g., STORE3 and STORE6), or a hub-based model where local transport is sufficient (e.g., STORE1 and STORE8). STORE2 and STORE5 focus on exploring, regulating, and building new storage and transportation infrastructure under moderate DAC demand. STORE2 supports both onshore and offshore development, while STORE5 is limited to onshore. STORE5, representing a low-scale option, enables DAC storage using existing onshore CO_2 storage sites in Alberta and Saskatchewan originally developed for point-source emissions. STORE4 builds on STORE5 by adding limited offshore storage capacity.

The pathways illustrated in the AP map show how policy packages can be sequenced to meet increasing DAC demand. The current situation becomes ineffective beyond 1 $MtCO_2$/year due to limited capacity in the carbon utilization market and the original intent of existing storage sites, which were developed for CCS. This creates a decision point. At this juncture, decision-makers could pursue longer-lived, more comprehensive options like STORE2, which has a sell-by condition of 200 $MtCO_2$/year and supports large-scale exploration and development of both offshore and onshore storage, or STORE7, with a sell-by condition of 150 $MtCO_2$/year, which focuses exclusively on onshore storage. Alternatively, decision-makers could opt for lower-cost but shorter-lived pathways such as STORE4, with a sell-by condition of 50 $MtCO_2$/year, or STORE6, with a sell-by condition of 30 $MtCO_2$/year. These rely more heavily on existing infrastructure and include only modest expansions—such as limited offshore development along the East or West Coast. Such strategies work if residual emissions (and therefore DAC demand) remains very low.

If DAC demand exceeds 150–200 $MtCO_2$/year, CO_2 storage would need to evolve into a large-scale industry, potentially combining different operational models depending on geographic focus (onshore vs. hybrid) and infrastructure approach (hub-based vs. distributed). Distributed models would require significantly more extensive CO_2 transport infrastructure, while hybrid models would necessitate enabling CO_2 delivery to offshore marine storage sites.

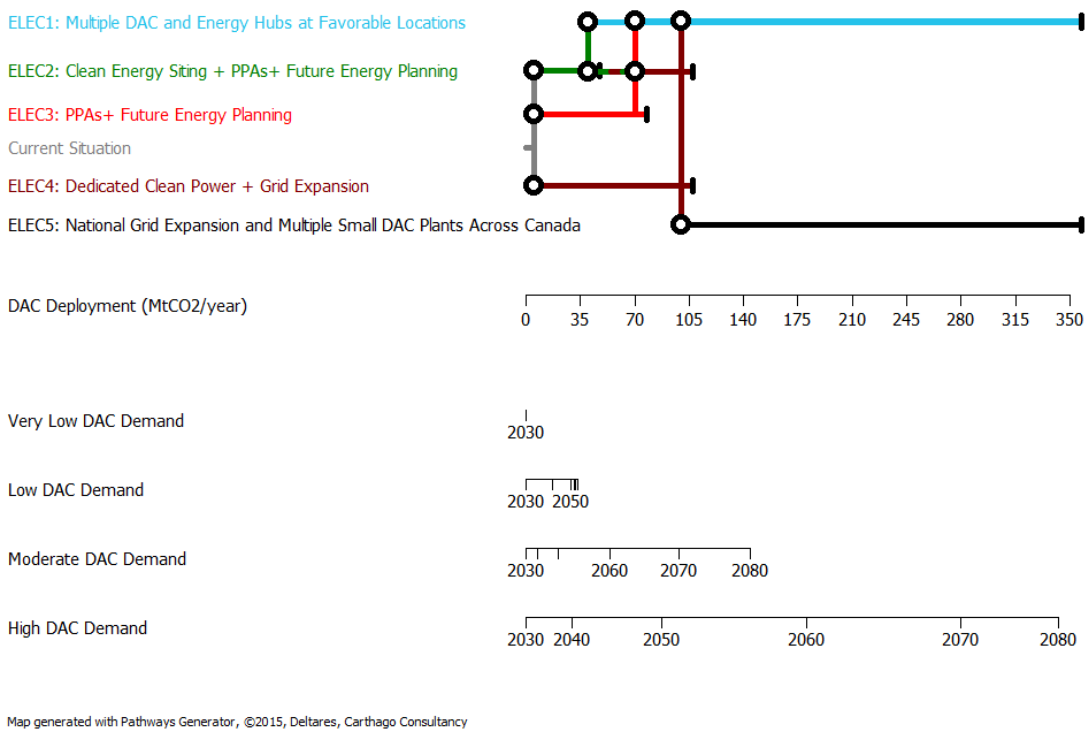

Figure 5-5. An adaptation pathway prototype for the electricity supply aspects of direct air capture deployment in Canada (EEU stands for "Explore, Expansion and Use")

Figure 5-6. An adaptation pathway prototype for the CO_2 storage

5.4 Conclusion and next steps

DAC is widely regarded as a necessary technology for addressing residual emissions in the pursuit of net-zero targets, and potentially for achieving net-negative emissions aligned with the 1.5°C climate goal. However, its future role is subject to deep, multidimensional uncertainty—arising from techno-economic factors such as cost trajectories and scalability, as well as socio-political factors including public acceptance and interprovincial policy alignment. One of the most critical sources of uncertainty is the scale at which DAC will be needed, which depends on the degree of decarbonization achieved, the volume of residual emissions, and DAC's competitiveness relative to other CDR methods. While energy-economy models are often used to guide policy decisions in this area, they primarily rely on techno-economic assumptions and frequently overlook broader contextual dynamics, potentially leading to misestimations of DAC's future role. Such misestimations, whether in the form of overestimation or underestimation, risk either wasting public resources or missing critical opportunities. To address this gap, this study integrates qualitative and quantitative approaches and visualizes results in a manner that supports "wayfinding" through sequential decisions fit for alternative futures. Importantly, the illustrative scenarios in the AP maps are not arbitrary. They are alternative quantified projections parameterized by the qualitative scenarios developed using the CIB method (discussed in Chapter 4), which transparently explored plausible DAC futures in Canada across a range of interacting descriptors, including DAC costs, pore space availability, access to low-carbon electricity, public acceptance, and policy coherence. These scenarios were then translated into quantitative pathways, to the extent permitted by available modeling tools, enabling estimates of DAC demand trajectories and energy requirements. A key advantage of this CIB-informed scenario modeling is its ability to transparently generate internally consistent narratives incorporating qualitative factors that can then be directly linked to quantitative outputs, improving both the scientific credibility and salience (or policy relevance) of the results.

While exploratory modeling and scenario analysis offer valuable insights into possible futures, they do not, on their own, provide guidance on how to act. The second part of this study addresses this gap by linking exploratory scenarios to decision-making processes. Specifically, the visualization afforded by AP maps demonstrates how to proactively respond to divergent DAC demand trajectories through policy planning across three critical dimensions: economics, electricity supply, and CO_2 storage. This linkage is particularly important, as varying DAC demand scenarios imply substantially different policy requirements and trajectories over the coming decades. To support this analysis, the AP approach was applied to map key policy options, identify potential failure points, and determine the timing of critical transitions. Although the primary aim of this study is to demonstrate the integrated use of exploratory

scenarios simulated with multiple drivers and the AP framework, even these preliminary applications yield valuable insights for policy planning related to DAC deployment. The three AP maps developed in this study highlight the need for early and regular monitoring of conditions that will affect DAC demand as well as coordinated policy planning across economic, electricity, and CO_2 storage dimensions to support scalable and adaptive DAC deployment in Canada. Economically, current policies may suffice only for limited deployment (~5 $MtCO_2$/year), with higher levels requiring a shift toward different incentives (e.g., CfDs, PTCs) or regulatory mandates, and eventually new governance models for net-negative emissions. On the electricity side, low levels of DAC pose few challenges, but scaling up introduces decision points where policymakers must choose between the expansion through a uniform national grid connection, decentralized regional systems, or self-supplied clean power strategies—each carrying implications for infrastructure build-up and local impacts. For CO_2 storage, early reliance on existing sites may be quickly exhausted if residual emissions do not correspond to the Very Low DAC Demand scenario (around 30 $MtCO_2$/year), prompting critical decisions about enabling offshore access, expanding onshore capacity, and investing in CO_2 transport infrastructure.

In the next phase of this ongoing research project, the identified policy pathways will be discussed and co-evaluated with relevant stakeholders to assess their perceived effectiveness, feasibility thresholds, and alignment with broader policy objectives. Such participatory consultations can help validate, refine, or discard specific pathways, while also revealing new policy options that were not identified in this analysis, which was primarily informed by a literature review and web search (see Section 5.3.5). While the AP maps presented in this study treat the economic, electricity, and CO_2 storage dimensions of DAC deployment separately for clarity and visualization, it is important to recognize that these dimensions are not independent in practice. Policy decisions in one dimension may enable or constrain choices in another. For example, adopting a high carbon price trajectory within the economic dimension could incentivize investment in cleaner electricity infrastructure, thereby influencing the viability of pathways in the electricity supply domain. In future research, it would be valuable to consult with policymakers to identify policy combinations across different dimensions that are mutually reinforcing, as well as those that may be incompatible or lead to unintended trade-offs.

Another key step for developing dynamic adaptive policy pathways involves the development and application of a scorecard—a structured evaluation tool commonly used in the AP approach—to compare policy pathways across multiple criteria. These criteria might include both monetary costs (e.g., government expenditures, capital investment requirements) and non-monetary factors, such as environmental outcomes, social acceptability, and institutional feasibility. Scorecards are displayed on the right side of Figure 5-1, illustrating how different pathways (e.g., the pathway of Action A versus

the pathway that begins with Action C and then shifts to A) yield distinct scores. In our example, one pathway may carry higher fiscal costs, another may encounter stronger public resistance, while a third could generate broader co-benefits such as job creation or regional equity. The scorecard enables transparent, multi-criteria comparisons and helps clarify trade-offs across divergent futures and stakeholder value systems.

Ultimately, the goal of the AP maps is to support policymakers in navigating the deep uncertainty surrounding the future of DAC, while still enabling timely and effective action. To do so, policymakers must monitor key indicators—some of which are scenario-dependent—that signal which future trajectory Canada may be heading toward. IAMs such as GCAM can also provide valuable insights by simulating potential futures and highlighting the timing of key events, including when DAC demands may begin to scale. Because transitioning between policy packages can require substantial lead time, early warning signals are essential for initiating timely responses. Several conditions can serve as monitoring triggers to anticipate future DAC demand. These include the success of decarbonization efforts and the resulting levels of residual emissions, the potential emergence of international mechanisms requiring countries to go beyond net-zero targets, evolving cost trajectories and public perceptions of DAC, and the comparative costs and scalability of alternative CDR methods. Monitoring these factors can help policymakers identify when current policies are approaching their limits and when more robust or adaptive interventions may be needed.

5.5 References

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Chapter 6
Conclusions, Limitations and Future Work

Direct Air Capture (DAC) is a carbon dioxide removal (CDR) technology that Canada may need in the future to meet its climate goals. However, the future of this technology remains deeply uncertain, and existing modeling studies and traditional decision-making approaches are not well equipped to support effective and adaptive policymaking under such conditions. This study examined the potential role of DAC with the overarching aim of supporting policymaking in Canada, addressing three major research gaps through its corresponding research objectives: (1) to understand the uncertainties surrounding the future of DAC by clarifying the full range of possible demand trajectories and their drivers through quantitative modeling; (2) to understand how different sources of uncertainty interact by developing coherent and internally consistent narratives of DAC's future in Canada; and (3) to inform decision-making under deep uncertainty by developing three decision-support tools across different dimensions of DAC that enable policymakers to navigate these divergent futures.

First, addressing Research Objective 1—understanding the uncertainties surrounding the future of DAC—the study provided the first comprehensive review of DAC deployment across IPCC global scenarios. It further complemented this review with a national-scale integrated assessment modeling analysis using the Global Change Analysis Model (GCAM), applied in a novel way to incorporate equity and burden-sharing considerations—an aspect often overlooked in existing research. This work, presented in Chapters 2 and 3, showed that DAC deployment is shaped by deeply uncertain and interacting drivers, including socio-economic pathways, the fossil-fuel dependence of future energy systems, and DAC's technology cost trajectories. When equity principles are applied, Canada's long-term CDR obligations rise sharply, making DAC and other CDR methods central to fairness-aligned pathways. These findings highlight the presence of both techno-economic and socio-political uncertainties (e.g., those related to international law), and because many socio-political and institutional factors cannot be adequately captured by quantitative models, Research Objective 2 examines these uncertainties and their interactions in a more systematic and integrated way.

Second, addressing Research Objective 2—understanding how different sources of uncertainty interact and developing coherent narratives of DAC's future in Canada—the study expanded beyond IAM-derived insights, such as the availability of low carbon electricity, cost of technology, and national CDR demand to include socio-political, regulatory, and governance factors that quantitative models cannot assess. Through a national expert workshop, Chapter 4 engaged experts to assess the interactions among a set of

critical uncertain drivers—such as DAC cost trajectories, access to clean electricity, CO_2 storage availability, public acceptance, and policy coherence—that had been identified prior to the workshop. These expert-elicited interactions were then analyzed using the Cross-Impact Balance (CIB) method to understand how different combinations of uncertainties could shape future DAC pathways in Canada. Applied systematically to DAC for the first time in Canada, the CIB analysis revealed reinforcing feedback loops among social perception, policy coherence, technology costs, and competitiveness—dynamics that can either enable DAC's expansion or significantly constrain its future. These interconnected uncertainties made clear that DAC's long-term role depends on complex socio-technical dynamics—insights that directly informed Research Objective 3, which focuses on designing adaptive strategies that remain effective across these divergent futures.

Third, supporting Research Objective 3—informing decision-making under deep uncertainty—the study connected the qualitative and quantitative insights by quantifying a subset of the CIB scenarios using GCAM, producing four DAC demand pathways (very low, low, moderate, and high). Chapter 5 then integrated these pathways into a Dynamic Adaptive Policy Pathways (DAPP) analysis, mapping policy actions and transition points across policies related to economics, electricity supply, and CO_2 storage dimensions. The results show that DAC demand in Canada could range from near-zero to over 300 $MtCO_2$/year by 2075, leading to vastly different policy and infrastructure needs. Low-demand futures can be supported by existing carbon pricing and investment incentives, whereas moderate-to-high futures require major interventions such as production tax credits, dedicated clean power, grid expansion, and large-scale CO_2 storage hubs.

Together, the three objectives form a logically connected research sequence: global and national modeling established what can be known about DAC-related uncertainties through quantitative analysis; expert elicitation and CIB analysis clarified how different sources of uncertainty interact; and the DAPP framework demonstrated what policymakers can do in response to these uncertainties. This integrated approach provides a robust decision-support framework that unites qualitative scenario discovery, quantitative scenario modeling, and adaptive planning to help navigate the complex uncertainties surrounding DAC deployment in Canada.

The following section summarizes the key methodological insights and case-specific findings, with additional details available in the individual conclusion sections of the aforementioned chapters.

6.1 Methodological Insights

In this study, three distinct methods were used in conjunction: quantitative scenario analysis using GCAM, qualitative scenario building using the CIB method, and the AP framework for communicating uncertainty and linking it to potential policies and strategies. Together, these approaches were used to explore diverse futures for DAC in Canada and to assess the effectiveness of different policy responses across a range of scenarios. Each method offers unique strengths, which are discussed in this section.

6.1.1 Integrated Assessment Models: Limitations and Best Practices

Quantitative energy-economy models such as IAMs (specifically GCAM in this study) are powerful tools for analyzing interactions across climate, energy, economic, and environmental systems. IAMs support both normative (goal-oriented) and descriptive (exploratory "what-if") scenario analyses, both of which have been influential in shaping global climate policy (Parson and Fisher-Vanden, 1997; Weyant, 2017). However, like any method, these approaches come with certain limitations and nuances in their application (Ackerman et al., 2009; Gambhir et al., 2019; Kriegler et al., 2015; Schneider, 1997; Van Asselt & Rotmans, 2002). The key issues most relevant to this study, along with the strategies we adopted to address them, are outlined below

First, IAMs often assume rational, utility-maximizing actors (Keppo et al., 2021). However, real-world decision-making frequently deviates from strict cost-minimization logic. In the case of DAC, for example, major corporate investments, the growth of voluntary carbon markets, and Canada's public procurement of carbon removals reflect motivations that extend beyond short-term least-cost considerations. These actions are driven by the anticipation that DAC will play a significant role in the future, and that near-term investments are essential to prepare for such a role. The AP framework—demonstrated through three prototypes in Chapter 5—broadens the set of plausible actions and policies that decision-makers might consider, even when these are not the most economically efficient options in the near term. The strength of the AP methodology lies not only in identifying no- or low-regret actions that can be taken today, but also in highlighting actions and policies that, if implemented prematurely, could lead to undesirable outcomes such as stranded assets.

Second, IAMs differ in the level of foresight they assume. Foresight refers to the extent to which decision-makers are presumed to anticipate the evolution of key techno-economic parameters (e.g., technology costs) and constraints (e.g., climate targets). Models range from fully myopic (no foresight) to perfect foresight—complete knowledge of future developments (Keppo et al., 2021). In practice, however,

decision-makers operate somewhere in between—often having a clearer view of short-term uncertainties than of those further into the future. Once again, the AP framework can serve as a valuable complement to IAMs by supporting adaptive policies that adjust over time as uncertainties unfold.

Third, IAMs often distribute mitigation burdens across regions based on technical or economic efficiency, rather than equity. This is especially problematic in global IAMs that optimize for a global climate target, such as a temperature goal or a remaining carbon budget. As a result, climate action, including decarbonization and CDR deployment, is allocated to regions with the greatest biophysical potential or lowest cost, rather than considering the differentiated responsibilities and nationally determined contributions embedded in the Paris Agreement (Dooley et al., 2021; Gidden et al., 2023; Jones, 2023; Motlaghzadeh et al., 2023). While one can check the global Paris-relevant scenarios and see the role of DAC and other CDR methods in a specific country/region such as Canada, it should be noted that those estimates in most cases do not have any logic other than contributing to a global target. To address this gap, Chapter 3 employs GCAM (a highly detailed IAM) with targeted modifications to simulate Canada's short- and long-term strategies for reaching net-zero, as well as its potential post-net-zero obligations under various burden-sharing principles rooted in international law and equity. This innovative application of IAMs, which incorporates post-net-zero responsibilities, enables the development of scenarios that are more relevant and anticipatory for Canadian policy-making (Motlaghzadeh et al., 2025). These scenarios offer a diverse range of futures for CDR technologies, supporting more informed and adaptive decisions.

Fourth, the structure of the model itself, namely which sectors are included, how technologies are represented, and the assumptions embedded in techno economic parameters, can significantly influence outcomes (Giarola et al., 2021; Realmonte et al., 2019). These modeling choices directly shape the conclusions and policy messages derived from scenario analysis. This is especially critical when decision makers use model outputs to justify financial investments, adopt or abandon policies, or support or withdraw from specific technological pathways. For instance, as discussed in Chapter 2, the IPCC AR6 scenario database includes pathways that achieve climate targets with a significant deployment of DAC (up to 40 $GtCO_2$ per year by 2100) as well as others that reach the same targets without any DAC deployment. One cannot conclude from either of these that DAC is definitively needed or not needed without first understanding the underlying narratives, modeling structures, and assumptions. If a model does not include DAC in its technology portfolio, or assumes prohibitively high DAC costs, the resulting deployment will naturally be zero or negligible. Model structure also affects perceived feasibility. When a

model includes only a limited set of technologies, it may compensate by over-relying on a narrow set of alternatives to meet climate goals, sometimes at deployment levels that are technologically infeasible or that carry significant environmental and socio-economic trade-offs (Motlaghzadeh et al., 2023). For example, land-based CDR options such as afforestation and BECCS can have large-scale implications for land, water, food, and biodiversity, impacts that could be reduced by expanding the modeled technology portfolio to include DAC and other options (Fuhrman et al., 2023; Motlaghzadeh et al., 2023). Chapter 3 deliberately explored a wide range of scenarios for Canada's future CDR deployment, including futures where DAC is widely available and low-cost, as well as those where it remains expensive or limited, while documenting the scenario logic and assumption in each case. This approach aims to help readers and decision makers better interpret the assumptions behind each scenario, not just for DAC but for the broader mitigation portfolio. In short, transparency in modeling assumptions, sensitivity analyses (especially for novel technologies with deeply uncertain costs and resource needs), and the use of models with rich and flexible technology representations can help address structural uncertainty to a meaningful degree.

Fifth, and more fundamentally, IAMs often struggle to incorporate key socio-political drivers that are difficult to quantify or model accurately (Prehofer et al., 2021; Symstad et al., 2017), such as public acceptance, political and regulatory coherence, or institutional dynamics. These factors not only influence outcomes independently but also interact with quantifiable variables (e.g., how public acceptance may affect technology costs or deployment speed). When such qualitative dynamics are excluded or only loosely approximated, there is a risk of oversimplifying the feasibility and realism of modeled pathways. To address this gap, Chapter 4 adopts a semi-quantitative scenario-building approach known as CIB analysis. The next subsection explores how CIB can serve as a foundation for more robust quantitative modeling by informing scenario design and bridging qualitative and quantitative insights.

6.1.2 Cross-Impact Balances for Qualitative Scenario Development: Strengths and Applications

CIB analysis enables the integration of both qualitative and quantitative scenario descriptors, factors that drive systemic change, by capturing their mutual influences using context-specific knowledge. These interdependencies can be informed through expert elicitation, literature review, or the informed judgment of scenario analysts (Weimer-Jehle, 2006, 2023). In the case of the DAC exercise, experts were asked to evaluate pairwise influences among key descriptors based on their domain expertise and familiarity with Canada's policy, technological, and societal contexts.

The CIB method systematically assesses the internal consistency of scenario combinations by analyzing whether the interactions among descriptors are mutually reinforcing. Internally consistent scenarios are those in which the specified conditions reinforce one another, thereby representing plausible future configurations of the system due to their stability. One of the core advantages of CIB is its ability to reveal futures that may not be immediately intuitive, by focusing on more accessible forms of knowledge, namely, the pairwise influences between system elements (Weimer-Jehle, 2006). Through this process, CIB not only filters out internally inconsistent combinations but also supports the transparent development of narratives that explain why a given scenario holds together (Lloyd & Schweizer, 2014; Schweizer, 2020).

These narratives play a crucial role in making complex futures more memorable and communicable. While quantitative outputs are indispensable for informing policy decisions, narratives add depth and context (Dillon & Craig, 2023; Moezzi et al., 2017; Veland et al., 2018), helping to bridge the gap between model results and real-world understanding. To this end, Chapter 4 presents the results of the CIB-based scenario discovery exercise, generating internally consistent qualitative narratives about Canada's potential DAC futures. One of the main findings of that chapter is that DAC's future success and competitiveness relative to other CDR methods is contingent on how the public perceives the technology, an aspect that cannot be captured through purely quantitative models. Building on this foundation, Chapter 5 demonstrates how CIB-informed narratives can be translated into quantitative projections. Using these narratives as a basis for modeling DAC demand and related sectoral outcomes enhances the interpretability of scenario results and provides a more holistic view of the drivers and constraints shaping each pathway.

For example, one of the scenarios developed, *Very Low DAC Demand*, illustrates a future in which Canada achieves net-zero emissions by 2050 and maintains this status through 2100. In this scenario, CDR plays a minimal role, limited to offsetting residual emissions from hard-to-abate sectors. These residuals are kept low through aggressive decarbonization, the widespread adoption of clean technologies, and societal shifts such as increased use of public transportation. High costs, limited CO_2 storage capacity, and potential public resistance to DAC further constrain its role. This narrative not only explains the low projected DAC deployment but also contextualizes it within a broader system of interacting social, economic, and technological drivers.

6.1.3 Adaptation Pathways as a Tool for Decision-Making Under Deep Uncertainty

While the previous sections outlined the value of using quantitative and semi-quantitative scenarios to explore plausible futures and understand underlying system dynamics, these approaches primarily serve to

inform the landscape of possibilities. From a decision-making perspective, the next logical step is to ask: How should we respond to these uncertainties? What constitutes a 'good' or 'wise' decision under such conditions?

In cases where uncertainties are well-characterized and probabilistic estimates can be assigned to different outcomes, traditional tools like cost–benefit analysis or expected utility maximization are commonly used to identify the optimal decision. However, problems characterized by deep uncertainty, such as the deployment of DAC, where uncertainty spans technological maturity, societal acceptance, policy support, and infrastructure readiness, assigning probabilities to future scenarios is neither feasible nor appropriate. In such contexts, all scenarios may be considered equally plausible, contingent on how various system elements evolve over time.

Poor decision-making practices under deep uncertainty include relying solely on median scenarios (which may not represent any actual trajectory) or planning exclusively around extreme scenarios (e.g., high DAC deployment). For instance, committing early to a high-DAC-demand future could lead to over-investment in DAC technologies at the expense of alternative solutions. Given finite resources, this may result in under-investment in other crucial technologies or strategies. If, over time, the drivers of high DAC demand fail to materialize, not only would resources have been misallocated, but climate targets could also be missed due to insufficient diversification.

To navigate such challenges, scholars have developed decision-support methods tailored to deep uncertainty. These methods generally focus on two key strategies: (1) identifying robust decisions—those that perform reasonably well across a wide range of plausible futures—and (2) adopting adaptive approaches that structure decisions as a sequence of steps, allowing flexibility to adjust as new information emerges (Haas et al., 2023; Hamarat et al., 2013; Lempert, 2019; Marchau et al., 2019). The latter requires a monitoring system to track how scenario conditions unfold over time, enabling early adjustments before pathways become constrained or locked in (Haasnoot et al., 2013).

The AP framework, applied in Chapter 5, aligns with the second strategy. Its strength lies in not only using scenarios to communicate uncertainty over time (via the "changing conditions" axis) but also linking specific policy options to those evolving conditions. The AP framework allows policymakers to visualize multiple pathways that all achieve the same objective (e.g., net-zero emission) but with different costs, co-benefits, and risks. This enables decision-makers to select strategies aligned with their values, worldviews (Lempert & Turner, 2021), and constraints, while maintaining flexibility to switch courses if necessary.

6.2 DAC-Specific Insights by Chapter

In addition to the methodological innovations developed throughout this study, which are applicable to a broad range of decision-making challenges under uncertainty, this research provides chapter-specific insights into CDR, particularly DAC, in the Canadian context. While each chapter includes detailed conclusions, this section synthesizes the most important findings across different chapters.

Chapter 2: Key uncertainties behind global projections of direct air capture deployment

- **Representation gaps:** DAC appears in fewer than half of the Paris-consistent AR6 scenarios, and where it does, assumptions about its costs and energy requirements vary widely.
- **Influential drivers:** DAC deployment levels are shaped by multiple interrelated factors in IAM scenarios. Socio-economic pathways (SSPs) influence key drivers such as energy demand, technological change, and emissions trajectories, with sustainability-oriented pathways (e.g., SSP1) generally requiring less DAC than fossil-intensive ones such as SSP5 (O'Neill et al., 2017). The continued use of fossil fuels increases residual emissions, often necessitating greater DAC deployment to meet climate targets. Temperature targets and overshoot allowances are also critical drivers. Pathways with lower levels of temperature overshoot typically require less CDR and DAC in the post-2050 period but demand more ambitious near-term mitigation efforts. Additionally, future DAC deployment is highly sensitive to the assumed cost trajectories of the technology, with lower costs significantly increasing its projected uptake.
- **Sustainability and feasibility concerns:** Heavy reliance on land-intensive CDR methods such as bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation (AR) raises significant sustainability concerns, including pressure on land, water resources, and food systems. In contrast, scenarios that include DAC often reduce dependence on BECCS and AR, thereby alleviating potential impacts on water availability and mitigating upward pressure on food prices.

Chapter 3: Applying equity principles leads to higher carbon removal obligations in Canada

- **Equity frameworks and Canada's carbon debt**: Applying equity principles such as Qualified Equal Per Capita (EPC-Q), which incorporates both historical responsibility and capacity to pay, and Per-Capita Convergence (PCC-Q), which considers current emission levels while gradually

converging toward a uniform global per-capita allocation, substantially increases Canada's carbon removal obligations. While the Net-Zero scenario requires modest CDR to balance residual emissions, equity-based scenarios demand significantly more. By 2100, cumulative CDR requirements rise from 7.5 $GtCO_2$ (Net-Zero) to over 20 $GtCO_2$ (EPC-Q). In these scenarios, DAC and Enhanced Weathering (EW) become central, with DAC alone reaching up to 8.7 $GtCO_2$, highlighting the scale of commitment needed to meet fairness-based global climate targets.

- **Infrastructure and feasibility challenges:** Achieving these elevated CDR targets domestically presents major feasibility challenges. Canada's geological storage requirements could exceed 850 $MtCO_2$/year by 2100, necessitating large-scale CO_2 transport networks and cross-sector planning. DAC would require up to 41% of natural gas and 9% of national electricity in some scenarios which would raise concerns about competing resource demands. Moreover, spatial mismatches between capture and storage sites, and the high degree of regional variability in energy supply, underscore the need for coordinated infrastructure investment and planning.
- **Pace of technological scaling:** The scale and pace of CDR deployment required under equity scenarios are ambitious, yet historically grounded. Modeled growth rates for DAC (7–8% average, up to 44% maximum) are comparable to the expansion of technologies like ammonia synthesis and biofuels in Canada. These parallels suggest that while rapid scaling is possible, it hinges on enabling policies, early investment, and overcoming initial techno-economic (e.g., current high costs of DAC) and potential socio-regulatory barriers (e.g., unsupportive regulatory environment during the formative phase.
- **Global versus local equity:** While equity-based frameworks promote global fairness, they may create localized burdens within Canada, particularly through land use conflicts, infrastructure siting, and public acceptance of technologies like DAC or BECCS. Policymakers must reconcile Canada's global responsibilities with domestic socio-political realities, ensuring that the transition to negative emissions does not exacerbate regional or community-level inequities.

Chapter 4: The future of direct air capture in Canada: a systematic scenario-based exploration of barriers and possibilities

- **Cost of DAC:** Despite its promise, DAC faces multiple interdependent barriers that must be addressed for it to become a viable CDR option in Canada. Chief among them are high capital and operating costs, which emerged in the CIB scenarios as a non-negotiable hurdle. Cost

reductions are essential but depend on both global learning and local enabling conditions, including access to clean electricity, materials, and CO_2 storage. Notably, costs are not purely techno-economic: they interact with public and political responses. For instance, high costs can provoke opposition if DAC is perceived as a misallocation of public funds, whereas cost reductions may improve public acceptance and policy viability under existing carbon pricing frameworks.

- **Infrastructure constraints:** The availability of low-carbon electricity and CO_2 storage is critical for DAC's competitiveness in Canada. While a high supply of clean electricity is a necessary condition, it is not sufficient on its own, especially when electricity must also serve broader decarbonization needs. Likewise, limited or poorly located geological storage can severely constrain DAC's scalability, particularly since much of Canada's existing storage capacity is already allocated to point-source carbon capture and storage projects.
- **Public perception and policy coherence:** Public acceptance and policy coherence emerged as two of the most decisive, yet often neglected, factors in enabling DAC in Canada. Even under favorable cost and energy conditions, public opposition or fragmented provincial policies can significantly hinder deployment. Concerns around land use, transparency, and the purpose of DAC (e.g., whether it supports genuine mitigation or delays it) must be proactively addressed. Securing a social license to operate will require early engagement, risk communication, and trust-building (Scott-Buechler et al., 2024).

Chapter 5: Adaptation pathways for direct air capture in Canada: a proposed framework for multi-sectoral responses to deep techno-economic and socio-political uncertainty

- **Deeply uncertain DAC demand projections:** To explore the range of potential DAC demand, four CIB narratives were selected for quantification using GCAM, resulting in a wide span of DAC deployment, ranging from 0 to 80 $MtCO_2$/year in 2050 and from 0 to 300 $MtCO_2$/year in 2075. All four scenarios achieve net-zero CO_2 emissions by 2050; however, the variation in DAC deployment by that year is driven by differences in residual emissions, which are influenced by the level of mitigation achieved and future energy demand. Additionally, the scale of DAC deployment depends on the role and availability of other CDR methods (such as BECCS, EW, and AR), and the relative competitiveness of DAC, which itself is shaped by factors such as DAC cost and available pore space. By 2075, the divergence becomes even more pronounced, partly due to

whether Canada adopts an international mandate to remove additional CO_2 for equity considerations and to help lower global temperatures to safer levels.

- **Economics of DAC:** Preparation for different DAC demand levels imply vastly different economic policy responses. At low deployment levels (~5 $MtCO_2$/year), Canada's current policy mix, such as carbon pricing, investment tax credits, and limited procurement, may suffice. However, to scale DAC to meet increased demand, more robust and differentiated policies become necessary. For example, moderate pathways require production tax credits and contracts for difference to improve market viability, while high deployment scenarios necessitate regulatory approaches like DAC mandates or public funding for net-negative emissions.
- **Electricity supply of DAC:** The electricity supply AP map outlines how policy responses must evolve as DAC deployment scales and electricity requirements increase. At low deployment levels (below 5 $MtCO_2$/year), electricity supply is not a major constraint. However, beyond this threshold, reached in most scenarios between 2034 and 2040, decisions about long-term electricity provisioning become critical. Three near-term pathways emerge: prioritizing DAC deployment in regions with clean grids and power purchase agreements, allowing DAC to operate regardless of grid carbon intensity, and requiring operators to build dedicated clean electricity sources. To scale DAC to meet further demand (> 5$MtCO_2$/year), two distinct structural models take shape: a centralized hub model focused on co-located low-carbon energy and storage infrastructure, and a distributed model requiring major grid expansions to connect DAC installations to clean energy sources and viable storage sites.
- **CO_2 storage:** Depending on the scale of DAC deployment and the corresponding need to sequester captured CO_2, different policy frameworks and infrastructure models may be required. Under the current situation, where CO_2 from DAC is primarily for utilization, such as the production of synthetic low-carbon fuels, deployment remains limited to less than 1 $MtCO_2$/year. For deployment levels up to approximately 30 $MtCO_2$/year, Canada could rely on existing or planned storage infrastructure originally developed for point-source emissions, while also exploring additional onshore and offshore storage options. At higher levels of DAC deployment (beyond 100 $MtCO_2$/year), four main storage models emerge, based on two key dimensions: the geographic scope (onshore only vs. hybrid onshore/offshore) and the infrastructure approach (distributed vs. hub-based). Distributed models involve DAC facilities located across the country, requiring long-distance CO_2 transport via pipelines or other mechanisms. In contrast, hub-based

models concentrate DAC and storage activities in a few strategic locations, minimizing the need for extensive transportation infrastructure. The choice among these models will depend on the scale of deployment, geographic factors, and policy priorities.

6.3 Limitations and Future Work

As with any research, this study has certain limitations stemming from project timelines and scope. This section outlines key limitations associated with the methodologies used in each chapter and identifies opportunities for future research. It is important to note that this study is part of a larger collaborative project, and some of the identified next steps will be pursued by other students and researchers in the coming years.

To quantify Canada's future demand for DAC, this study utilized GCAM, a technology-rich IAM that includes three DAC technology variants in its portfolio. Given the focus on carbon budget constraints, our modeling emphasized net-zero CO_2 emissions, rather than net-zero *GHG* emissions. Future Canadian studies could extend this scope to include non-CO_2 greenhouse gases, offering a more complete picture of mitigation requirements and implications for CDR deployment. While GCAM is a global model, Canada was treated as a distinct region, enabling us to model national-level climate targets and assess both net-zero and post-net-zero obligations. However, the model does not capture provincial-level differences. Future work could build on GCAM-Canada, a customized version of GCAM with provincial resolution (Bergero et al., 2022; Younis et al., 2025), and incorporate a broader portfolio of CDR technologies to avoid unsustainable reliance on individual methods (Fuhrman et al., 2023). This would enable researchers to explore how provinces with geological storage potential (such as Alberta and Saskatchewan) might pursue more DAC and BECCS, while others, such as Atlantic provinces, might focus on marine-based CDR due to their coastal access. These insights could support the development of region-specific AP maps and inform geographically tailored policy responses.

In addition, carbon utilization technologies, while currently limited in market size, were not included in our modeling. Their integration into future analyses could offer valuable insights into early-stage DAC scale-up by introducing revenue-generating opportunities for companies. Finally, uncertainty also arises from structural assumptions within IAMs themselves. Future research would benefit from multi-model comparison exercises to assess DAC deployment across different modeling frameworks, thereby improving the robustness and credibility of insights. International cooperation on CDR, such as through

credit trading or cooperative approaches under Article 6 of the Paris Agreement, also warrants further exploration in the Canadian context.

In the qualitative portion of this research, CIB analysis was conducted to explore socio-political and techno-economic uncertainties affecting DAC's future in Canada. While this method provided internally consistent scenario sets and valuable insights into system interdependencies, certain features of the CIB methodology were not fully explored. For example, *succession analysis*, which traces system evolution from an unstable (internally inconsistent) scenario toward a stable one, could provide strategic insights for transition planning. Likewise, *intervention analysis* could help identify targeted changes that shift the system from an undesirable to a more desirable future scenario through policy or technological interventions. Given that CIB is grounded in systems theory, its full potential lies in supporting dynamic, policy-relevant insights that go beyond static scenario generation. Future applications of CIB could further leverage these analytical features to inform actionable transition pathways for DAC under uncertainty.

Chapter 1 aimed to explore how three distinct methods of CIB, integrated assessment modeling using GCAM, and the AP framework can be meaningfully combined to inform decision-making under deep uncertainty. To illustrate this integration, prototype AP maps were developed for three critical dimensions of DAC deployment: economics, electricity supply, and CO_2 storage. These initial maps serve primarily as illustrative examples, with future work expected to produce more detailed and comprehensive versions. Additional dimensions (e.g., material supply) also warrant examination, as they may present unique constraints and require tailored policy responses depending on the scale of DAC deployment.

While each AP map was presented separately to enhance clarity and visualization, it is important to acknowledge that these dimensions are deeply interconnected. Policy choices in one domain may enable or restrict pathways in another. For example, implementing a high carbon price trajectory in the economic dimension could incentivize cleaner electricity infrastructure, thereby shaping options in the energy supply domain. Recognizing and accounting for these interdependencies will be essential in the next phase of research and policy design. In the next phase of this project, a systematic examination of these interdependencies is recommended, along with the development of practical guidance to navigate and manage them effectively.

In addition, the proposed policy pathways will be co-evaluated with Canadian stakeholders using a structured scorecard approach, which enables transparent comparison across multiple dimensions, such as financial costs, social acceptability, and institutional feasibility. Some strategies may prove cost-effective

but encounter public opposition, while others may gain broader social support yet require greater government expenditure.

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Appendix A
Supplementary Information of Chapter 2

Motlaghzadeh, K., Schweizer, V., Craik, N., & Moreno-Cruz, J. (2023). Key uncertainties behind global projections of direct air capture deployment. *Applied energy*, *348*, 121485.

A1. Direct air capture technology review

DAC removes CO_2 from the ambient air (CO_2 concentration of 410 ppm) by a relatively similar technological approach to post-combustion CO_2 scrubbing systems. The main distinction between these two systems is that DAC technologies collect carbon dioxide from ambient air rather than exhaust emissions with higher CO_2 concentrations. Depending on the source, CO_2 concentration in flue gas might be between 1% (10,000 ppm) for aluminum production to 33% (330,000 ppm) for cement production (Wang & Song, 2020). The high costs and energy requirements of DAC arise from this difference, as capturing CO_2 from ambient air with dilute concentrations increases energy requirements approximately three-fold (Erans et al., 2022). While it is possible to use physical materials to capture CO_2 when its concentration is high, binding CO_2 from dilute gas (around 400 ppm) is only feasible using chemical materials that react with CO_2, such as hydroxide and amines. Two types of chemical sequestration materials are liquid solvents (in the form of aqueous solutions) and solid sorbents. When solvents (HT-DAC) and sorbents (LT-DAC) are saturated with CO_2, they should be prepared for other cycles of carbon capture, a process that is called "regeneration". Liberating CO_2 from sorbents/solvents and producing a concentrated stream is an endothermic process. While all technologies capture carbon by contacting air with some sorbent material (liquid solvent for HT-DAC and solid sorbent for LT-DAC) that selectively binds the CO_2, they are significantly different regarding their impacts on the materials supply chain, energy requirements, environmental footprint, modularity, maturity and their projected costs, both for capital expenditures (CAPEX) and annual operational expenditures (OPEX) (Deutz & Bardow, 2021; Fasihi et al., 2019; Madhu et al., 2021; Qiu et al., 2022). Below are some insights from different life cycle assessment studies that investigated the differences between technological configurations of DACCS:

Energy Supply Sources: Depending on the type of technology, various sources of energy supply, both for heat and electricity, might be available. Since LT-DAC needs a relatively lower temperature (around 80 to 120 °C) of heat energy compared to HT-DAC (above 800 °C), the required heat energy

can be supplied from different sources, such as industrial low-grade waste heat, renewables, heat pumps and geothermal (Beuttler et al., 2019; Broehm et al., 2015; Deutz & Bardow, 2021; Fasihi et al., 2019; Ishaq & Crawford, 2022; Qiu et al., 2022). On the other hand, 800-900 °C thermal energy cannot be provided by using second-hand energy (Broehm et al., 2015); therefore, options for HT-DAC are currently limited to using natural gas or biomethane (Qiu et al., 2022). Depending on the energy source, the net removed CO_2 rate might change due to emissions associated with supplying the energy. Due to the differences mentioned above, models must consider both types of relatively mature DACCS technologies (HT- and LT-DAC). DACCS deployment might change temporally and spatially because of energy supply feasibility and atmospheric greenhouse gas concentrations. For instance, areas with plenty of gas resources might favor HT-DAC. At the same time, regions with some cheap industrial waste heat or cheap renewable energy resources might prefer LT-DAC. From the modeling perspective, it should be noted that having LT-DAC as an element that requires renewable energy might also make the deployment pace of renewables at a higher rate, which in turn might be challenging in the real world.

Water Consumption: The water consumption of HT-DAC (aqueous hydroxide solution) is between 3 to 12 times higher than LT-DAC (solid amine-based sorbents) for each ton of removed CO_2, primarily due to the higher evaporation rate associated with the process (Qiu et al., 2022). Moreover, under some conditions, LT-DAC might produce water as a by-product that can be utilized for other purposes (Beuttler et al., 2019). Fasihi et al. (2019) investigated the water consumption rates associated with three DACCS designs consisting of one HT-DAC design (Carbon Engineering design by Keith et al. 2018 (Keith et al., 2018)) and two LT-DAC designs (by Climeworks and Hydrocell). The water consumption estimations were 4.7 tons for HT-DAC and 0.8 to 2 tons for Climework's LT-DAC design for each ton of captured CO_2. In the regeneration process of Hydrocell's LT-DAC design, 1.9 tons of water was produced (rather than consumed) when capturing one ton of CO_2 (Fasihi et al., 2019). These estimates are much lower than the water consumption of BECCS, which is 300 to 750 tons of water/tCO2, depending on the crop or forest characteristics (Smith et al., 2016). It is crucial to incorporate direct and indirect water consumption (as well as land use) associated with CO_2 removal and storage by DACCS (and other CDR methods), which can be derived using life cycle assessment (LCA) practices (Goglio et al., 2020; Jeswani et al., 2022; Madhu et al., 2021; Terlouw et al., 2021). The indirect water consumption of DACCS includes infrastructure construction and end-of-life disposal, sorbent (or solvent) production and disposal, transfer and storage of captured CO_2, and

electricity and heat demand. The scale that these water-consumptive steps contribute to the total water consumption and how it might change in the future (due to scaled-up DACCS) vary between HT and LT-DAC (Madhu et al., 2021). Madu et al. (2021) found that for both HT-DAC and LT-DAC, when low-carbon-energy sources (namely solar heat and wind-dominated electricity) are used to supply energy for DAC, the water consumption of DAC will increase at a scale of three to five. The reason behind the rise in water consumption is the additional water-requiring stages added by the introduction of additional low-carbon-energy sources (Madhu et al., 2021). Some examples can be the water consumed by quartz mining, cell manufacturing and transmission for solar PV (Harto et al., 2010), building materials of turbines for wind power (Yang & Chen, 2016) and irrigation for bioenergy crops (Li et al., 2021)

A2. Interactions among different CDR methods

Figure A1 shows the differences between BECCS deployment in scenarios with DACCS as an available option and those that do not include this method. We can see that the median BECCS deployment is lower when DACCS is an available option.

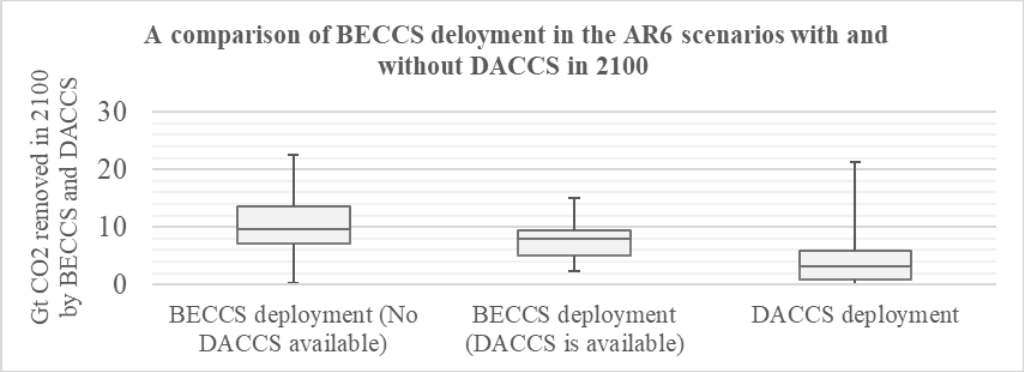

Fig A1. A comparison of BECCS deployment in scenarios with (177 scenarios) and without DACCS (469 scenarios) in 2100

Figure A2 shows the differences between DACCS deployment in scenarios with AR as an available option and those that do not include this method. We can see that the median DACCS deployment is lower when AR is an available option.

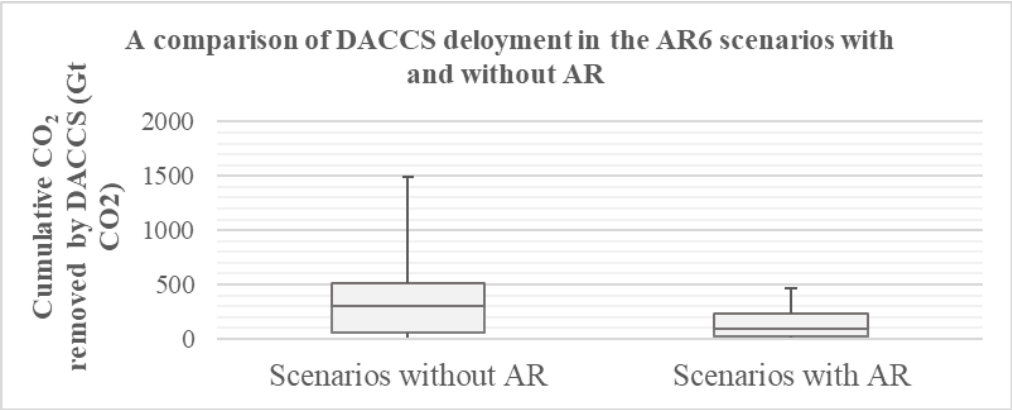

Fig A2. A comparison of DACCS deployment in scenarios with and without afforestation/reforestation (AR)

A3. Elements of different shared socio-economic pathways (SSPs)

As section 4.2 of the main article discusses, different shared socio-economic pathways (SSPs) have distinct elements that might affect the deployment of direct air capture (and other carbon removal methods). Some of those scenario elements collected from studies are provided in Table A1.

Table A1. Elements and characteristics of different shared socio-economic pathways

SSP element	Global Shared Socio-economic Pathways (SSPs)				
	SSP1 (van Vuuren et al., 2017)	SSP2 (Fricko et al., 2017)	SSP3 (Fujimori et al., 2017, p. 3)	SSP4 (Calvin et al., 2017, p. 4)	SSP5 (Kriegler et al., 2017, p. 5)
Social cohesion, participation and equity (O'Neill et al., 2017)	*High*	*Medium*	*Low*	*Low and medium (for equity)*	*High*
International trade (O'Neill et al., 2017)	*Moderate*	*Moderate*	*Constrained*	*Moderate*	*High*
Globalization(O'Neill et al., 2017)	*Connected Markets*	*Semi-opened globalized economy*	*De-globalizing regional security*	*Globally connected elites*	*Strongly globalized*
International cooperation(O'Neill et al., 2017)	*Effective*	*Relatively weak*	*Weak*	*Effective for globally connected, not for vulnerable populations*	*Effective for development goals not*

SSP element	Global Shared Socio-economic Pathways (SSPs)				
	SSP1 (van Vuuren et al., 2017)	SSP2 (Fricko et al., 2017)	SSP3 (Fujimori et al., 2017, p. 3)	SSP4 (Calvin et al., 2017, p. 4)	SSP5 (Kriegler et al., 2017, p. 5)
					environmental ones
Environmental policy (O'Neill et al., 2017)	*Improved management of local and global issues; tighter regulation of pollutants*	*Concern for local pollution but moderate action*	*Low priority for environmental issues*	*Focus on the local environment and pay little attention to vulnerable areas*	*Focus on the local environment with little concern for global problems*
Technology development (O'Neill et al., 2017)	*Rapid*	*Medium, uneven*	*Slow*	*Rapid in high-tech economies/sectors and slow in others*	*Rapid*
Technology transfer (O'Neill et al., 2017)	*Rapid*	*Slow*	*Slow*	*Not significant within countries*	*Rapid*
Energy tech change (O'Neill et al., 2017)	*A shift from fossil fuels to renewables and efficiency*	*Overall reliance on fossil fuels but with investments in renewables*	*Domestic Energy Sources*	*Investment in efficiency and low-carbon sources*	*Directed toward fossil-fuels*
Renewable energy cost reductions (Fujimori et al., 2017, p. 3)	*High*	*Medium*	*Low*	*High*	*Low*
Preference for fossil-fired power plants (Fujimori et al., 2017, p. 3)	*Low*	*Medium*	*High*	*Medium*	*High*

Table A2 shows the differences between the SSP baseline (no climate policy) scenarios simulated by five integrated assessment models (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kc & Lutz, 2017; Kriegler et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017). As we can see, the

population and GDP assumptions vary significantly in different SSPs. In addition to these factors, the underlying socio-economic narratives of each SSP lead to different pathways for final energy demand and supply sources. Because of these differences, SSPs lead to varying global warming levels. While an SSP1 baseline scenario reaches around 3 °C in 2100, the SSP5 world is expected to have a warming level of about 5°C. These differences in baseline SSPs also contribute to the distinct pathways of CDR or DACCS deployment.

Table A2. Social, Energy and Climatic Characteristics of baseline SSPs

Variable	Baseline Shared Socio-Economic Pathway (SSP)				
	SSP1	SSP2	SSP3	SSP4	SSP5
	Modeled by				
	IMAGE	MESSAGE-GLOBIOM	AIM/CGE	GCAM4	REMIND-MAgPIE
Population of 2100 (Million)	6957.99	9032.42	12620.14	9292.45	7375.00
GDP|Purchasing Power Parity (billion US$2005/year)	565389.63	539332.40	270265.00	352091.46	1031000
Final Energy (EJ/year$_{2100}$)	528.31	973.84	778.98	706.77	1167.00
Oil (EJ/year$_{2100}$)	54.23	298.61	204.84	202.34	195.80
Gas (EJ/year$_{2100}$)	217.24	347.23	256.12	210.28	446.50
Coal (EJ/year$_{2100}$)	115.58	359.09	542.82	218.19	888.20
Geothermal/Other (EJ/year$_{2100}$)	6.09	0.01	0.54	3.57	6.87
Hydro (EJ/year$_{2100}$)	26.29	24.93	28.97	21.46	35.99
Nuclear (EJ/year$_{2100}$)	0.13	45.33	6.58	63.55	32.91
Biomass (EJ/year$_{2100}$)	137.35	65.66	168.19	110.79	74.90
Solar (EJ/year$_{2100}$)	117.85	78.95	2.44	47.40	80.89
Wind (EJ/year$_{2100}$)	31.80	84.51	4.69	25.99	62.23
Emissions ($MtCO_2$/year$_{2100}$)	24612.91	85684.20	85214.97	44784.72	126097.68
Global Warming (°C) in 2100	3.02	3.76	4.07	3.76	5.05

Color bars represent the relative value of cells in each row (variables). Longer bars indicating higher values and shorter bars indicating lower values. The length of the bars is determined by the scale of values in each row.

A4. Carbon price and the changes in CDR deployment among scenarios

Another factor that makes the cost projections of DACCS important is the carbon pricing trajectory that IAMs use as a proxy for different climate policies. Introducing alternative carbon prices (rather than allowing models to produce exponential pathways to meet climate targets endogenously) not only influences the total CDR deployment but also affects the deployment scale of DACCS specifically. This is because DACCS is currently more expensive than CDR methods such as BECCS and enhanced weathering, which makes models prefer them at lower carbon prices. This phenomenon is observed in

scenarios by Strefler et al. (2020a) and (2020b), where we can see significant variations in DACCS deployment (S28 to S37). Among the SSP2 scenarios that meet 1.5 °C, S36 has the minimum DACCS deployment in 2100 (32 $MtCO_2/year_{2100}$). In this scenario, the carbon price peaks at 2045 (475 US$2010/t CO_2) and stays constant for the rest of the century. Following this carbon price trajectory, DACCS deployment peaks around 2055 (901 $MtCO_2/year_{2055}$) and then decreases to 32 $MtCO_2/year_{2100}$. Looking at 2100, cheaper CDR methods such as BECCS and enhanced weathering dominate the CDR portfolio. The CO_2 pathways associated with scenarios by Strefler et al. (2021a) and (2021b) and CDR deployment details are shown in Figure A3.

Table A3. The differences in population and energy characteristics of scenarios (Fuhrman et al., 2020, 2021; Marcucci et al., 2017; Strefler, Bauer, et al., 2021; Strefler et al., 2018; Strefler, Kriegler, et al., 2021)

	Model	Scenario ID	Population (2100)	Final Energy (EJ/Year2100)	Biomass (EJ/Year2100)	Wind (EJ)	Hydro (EJ/Year2100)	Geothermal (EJ/Year2100)	Solar (EJ/Year2100)	Nuclear (EJ/Year2100)	Coal (EJ/Year2100)	Oil (EJ/Year2100)	Natural Gas (EJ/Year2100)	DAC (MtCO2/Year2100)	BECCS (MtCO2/Year2100)	CDR (MtCO2/Year2100)
SSP2-1.5°C	MERGE-ETL 6.0	S1	10107.2	947.6	300.0	216.6	47.0		282.6	67.7	91.4	55.0	120.0	38259.1	14413.7	52672.8
	REMIND1.7	S5	9012.2	835.6	183.7	148.3	34.9	47.7	744.1	28.7	0.5	3.5	0.5	3549.2	6042.5	12000.0
	REMIND1.7	S6	9012.2	900.2	195.6	171.1	33.2	47.6	810.9	28.8	1.3	4.4	25.7	10779.3	6894.0	20000.0
	REMIND1.7	S7	9012.2	809.9	152.5	152.7	33.4	47.6	717.6	30.3	0.2	2.9	0.0	2110.0	4602.4	8000.0
	GCAM 5.2	S24	9024.5	637.1	203.3	88.7	21.6	4.0	113.2	126.0	88.0	133.8	671.2	23291.4	10629.6	33921.0
	GCAM 5.2	S25	9024.5	660.7	181.8	83.4	21.6	4.0	106.0	112.1	98.9	161.8	624.3	29096.2	8912.7	38008.9
	GCAM 5.2	S26	9024.5	641.9	197.5	84.4	21.6	4.0	108.6	106.4	78.2	132.2	477.1	10521.8	9946.7	20468.4
	GCAM 5.2	S27	9024.5	663.3	178.3	81.0	21.6	4.0	103.5	100.0	89.2	157.9	493.3	16137.1	8280.1	24417.2
	REMIND 2.1	S28	9019.7	722.4	228.4	246.3	34.9	27.5	473.5	34.4	2.1	13.5	41.2	6110.3	10654.6	16764.9
	REMIND 2.1	S33	9019.7	648.3	161.8	188.1	34.7	27.0	320.1	26.0	10.0	58.4	92.5	21.4	7486.1	7507.5
	REMIND 2.1	S31	9019.7	734.1	231.4	275.7	35.2	27.8	485.7	29.3	0.2	16.5	21.3	7294.0	11262.9	18556.9
	REMIND 2.1	S29	9019.7	740.8	227.6	280.4	35.1	28.4	486.6	29.3	0.2	19.6	21.9	7552.3	11074.3	18626.6
	REMIND-MAgPIE 2.1-4.2	S35	9019.7	675.3	170.2	194.9	34.5	29.4	348.6	20.2	1.2	62.9	92.4	32.6	7888.0	10502.5
SSP2- 2°C	MERGE-ETL 6.0	S2	10107.2	821.3	300.0	165.7	48.1		235.6	45.5	72.5	23.3	136.1	21363.5	14752.1	36115.6
	REMIND1.7	S10	9012.2	786.5	213.9	135.8	34.4	52.6	641.4	25.9	1.3	5.0	7.7	0.0	6074.8	8000.0
	REMIND1.7	S9	9012.2	900.0	218.1	150.7	34.6	49.5	725.4	26.4	3.3	11.4	85.1	9284.9	8306.8	20000.0
	REMIND1.7	S8	9012.2	793.8	226.1	137.3	35.2	48.6	637.2	27.3	1.9	5.8	19.5	1281.9	8309.8	12000.0
	REMIND 2.1	S32	9019.7	691.1	206.5	199.8	34.5	30.9	334.7	20.5	5.7	56.9	107.1	1410.3	10210.6	11620.9
	REMIND 2.1	S34	9019.7	669.9	166.8	194.1	33.5	29.4	319.0	23.1	10.8	67.5	95.4	8.4	8154.2	8162.6
	REMIND 2.1	S30	9019.7	700.6	208.1	201.4	34.3	31.2	340.0	20.5	2.9	54.0	121.6	2452.8	10381.5	12834.3
	REMIND-MAgPIE 2.1-4.2	S37	9019.7	677.3	156.5	192.7	34.2	29.4	335.8	21.2	3.6	67.2	102.8	1.5	7147.4	9494.7
	GCAM 5.3	S46	9130.2	614.9	307.2	134.0	21.7	3.9	158.0	97.9	10.4	30.8	106.2	9475.9	15360.8	24836.6

For each variable (columns, such as population, CDR, etc), green color bar ranges is used to indicate the relative values of cells in the column. The **darker green** shades indicate higher values, while the **lighter green** shades indicate lower values.

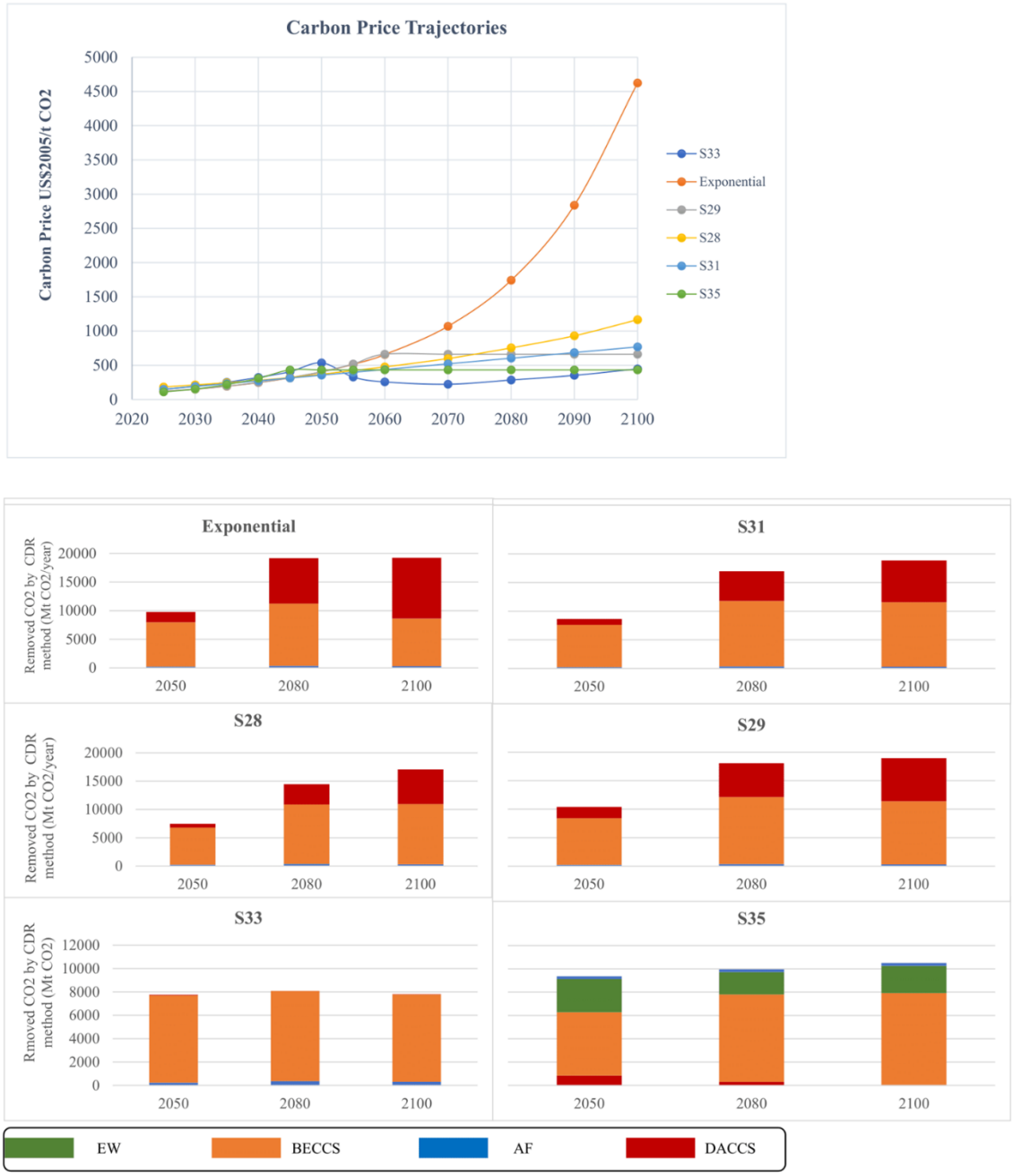

Fig A3. Carbon price trajectories and CDR deployment for some of the scenarios of the studies by Strefler, Bauer, et al., (2021); Strefler, Kriegler, et al., (2021)

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Appendix B
Supplementary Information of Chapter 3

Motlaghzadeh, K., Craik, N., Moreno-Cruz, J., Schweizer, V., Fuhrman, J., & Hipel, K. W. (2025). Applying equity principles leads to higher carbon removal obligations in Canada. *Communications Earth & Environment*, *6*(1), 88.

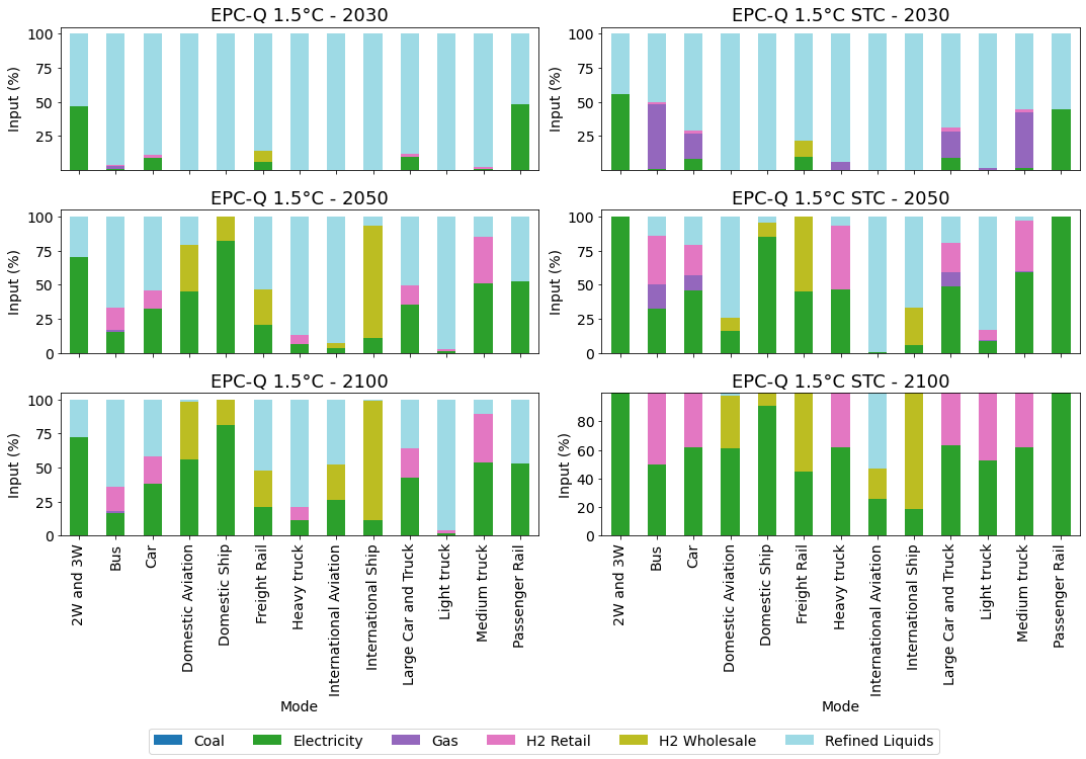
B1. Decarbonization in the transportation sector

Supplementary Fig. 1 illustrates the contribution of different energy inputs (e.g., coal, electricity, gas, refined liquids) to various transportation modes for the years 2030, 2050, and 2100, across two key scenarios: EPC-Q 1.5°C, our most ambitious scenario, and EPC-Q 1.5°C with socio-technological change (STC), which was analyzed in the sensitivity analysis of future energy pathways (Section 3.2.5).

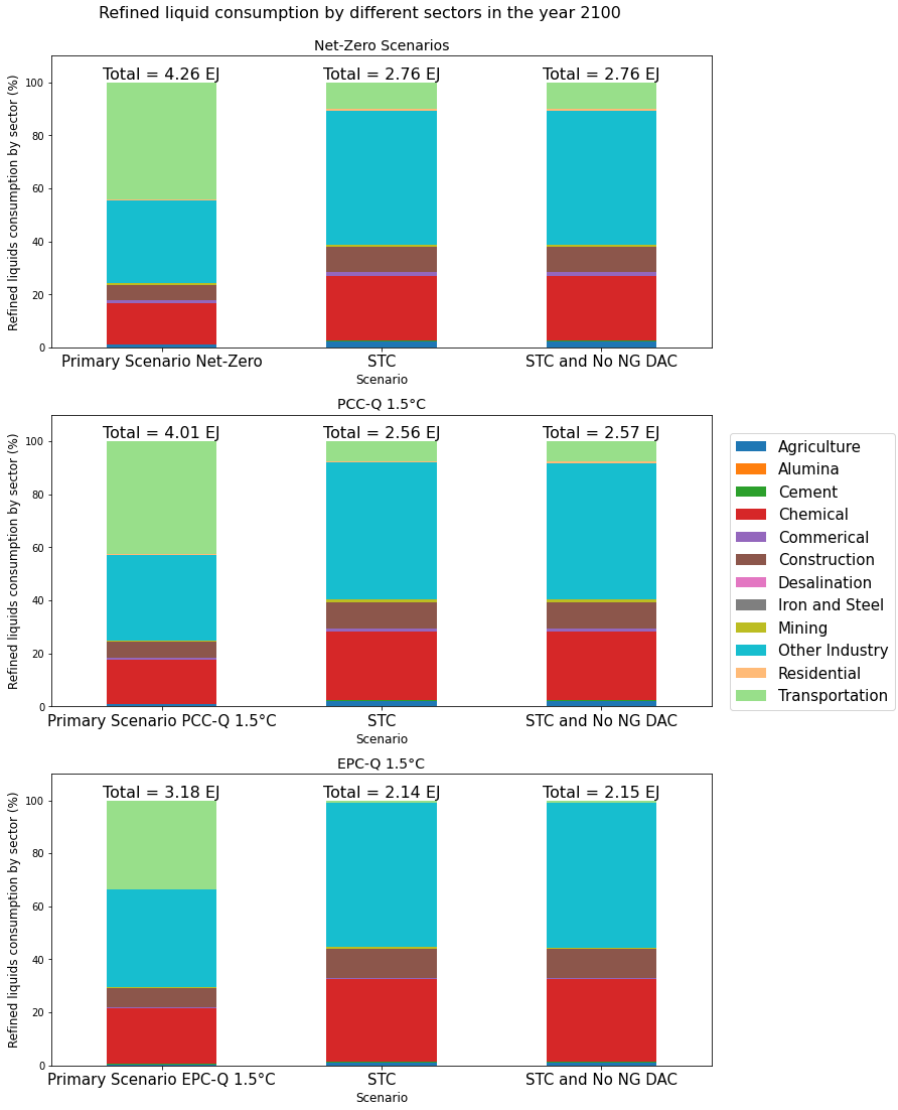
In 2050, the year when net zero is achieved in the primary scenario, residual emissions from the transportation sector remain at 61 $MtCO_2$. However, in the STC, these emissions drop to 31 $MtCO_2$. By the end of the century, in 2100, the divergence between the two scenarios becomes even more pronounced: the primary scenario still results in 30 $MtCO_2$ of emissions, while the STC scenario almost fully decarbonizes the transportation sector, leaving only 0.41 $MtCO_2$ of residual emissions. To understand the drivers of such deep decarbonization in the STC scenario, we can examine the last row of Supplementary Fig. 1 (the year 2100). Comparing the first column (primary EPC-Q scenario) with the second column (STC scenario), we see a stark contrast in energy inputs for different transportation modes. For example, in modes like cars and heavy trucks, the energy mix in the primary scenario includes both refined liquids and electricity. In contrast, in the STC scenario, these modes are almost entirely powered by hydrogen and electricity. This highlights a key point: the STC scenario facilitates substantial decarbonization in the transportation sector, driven by a widespread shift to alternative energy sources across different transportation modes.

In Section 3.2.2 of the main text, we observed that refined liquids continue to contribute to final energy demand, even late in the century. In this section, as illustrated in Supplementary Fig. 2, we break down the sectors that rely on refined liquids for their operations. The results cover the primary scenarios—Net-Zero 2050, EPC-Q 1.5, and PCC-Q 1.5—as well as the STC-based scenarios discussed in Section 3.4.3 of the paper. In the STC scenario, we see a significant reduction in the transportation

sector's reliance on refined liquids, with much of its energy being supplied by hydrogen and electricity. However, even in these highly decarbonized scenarios, between 2.14 and 2.7 EJ of final energy is still supplied by refined liquids, mainly for industrial processes, chemical production, and construction.



Supplementary Figure 1. Transportation activity by mode and energy input in different scenarios for the years 2030, 2050 and 2100



Supplementary Figure 2. Refined liquid consumption by different sectors in the year 2100

GCAM Carbon capture rates

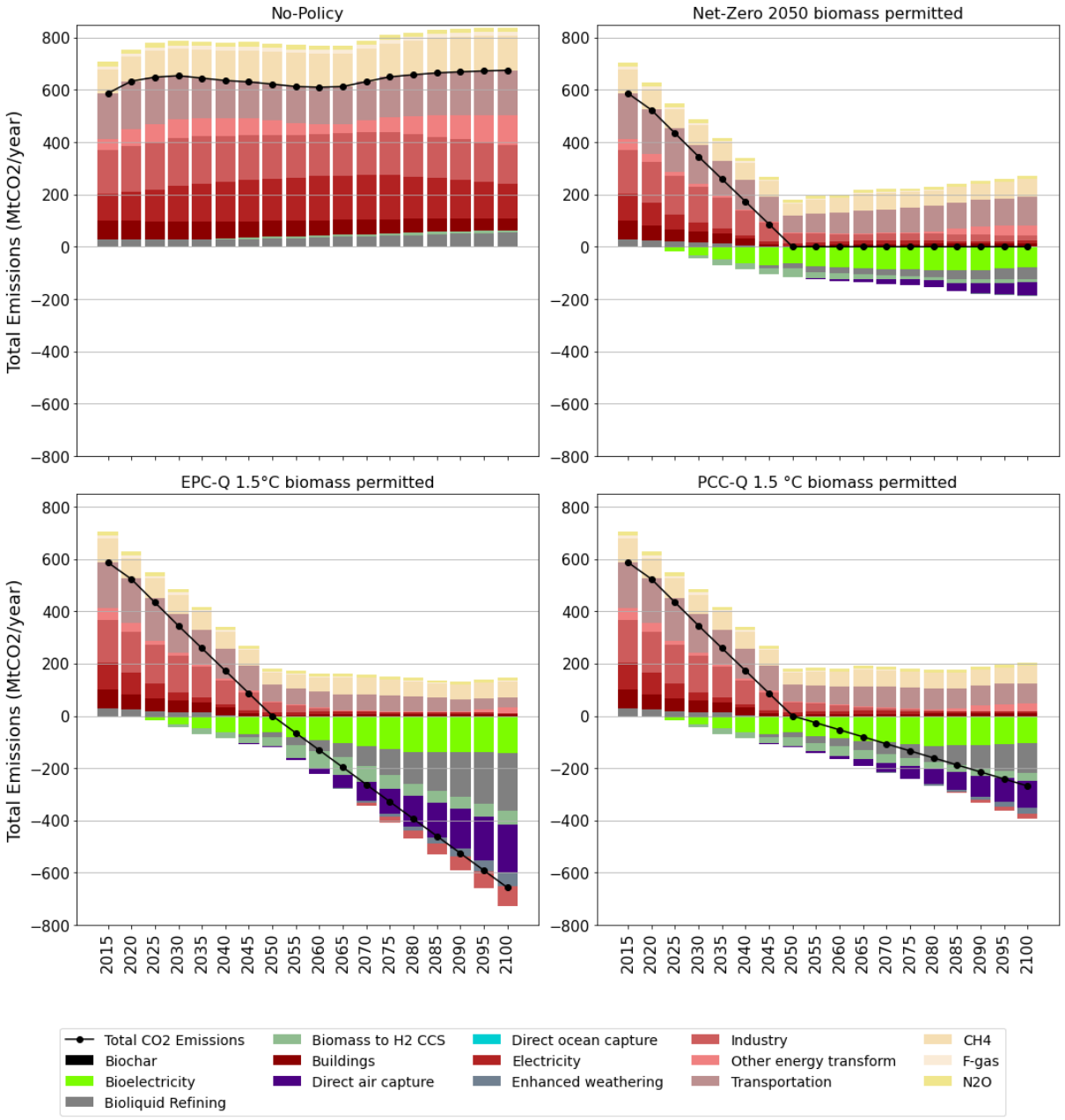
GCAM assumes that Carbon Capture and Storage (CCS) technologies will mature sufficiently later in the century to enable high rates of CO_2 capture. Supplementary Table 1 presents the assumed CO_2 removal fractions for various technologies when CCS is integrated into different processes. This table is Table 5 of GCAM documentation, available at https://jgcri.github.io/gcam-doc/v3.2/The_Energy_System)

Supplementary Table 1. Carbon capture rates by technology

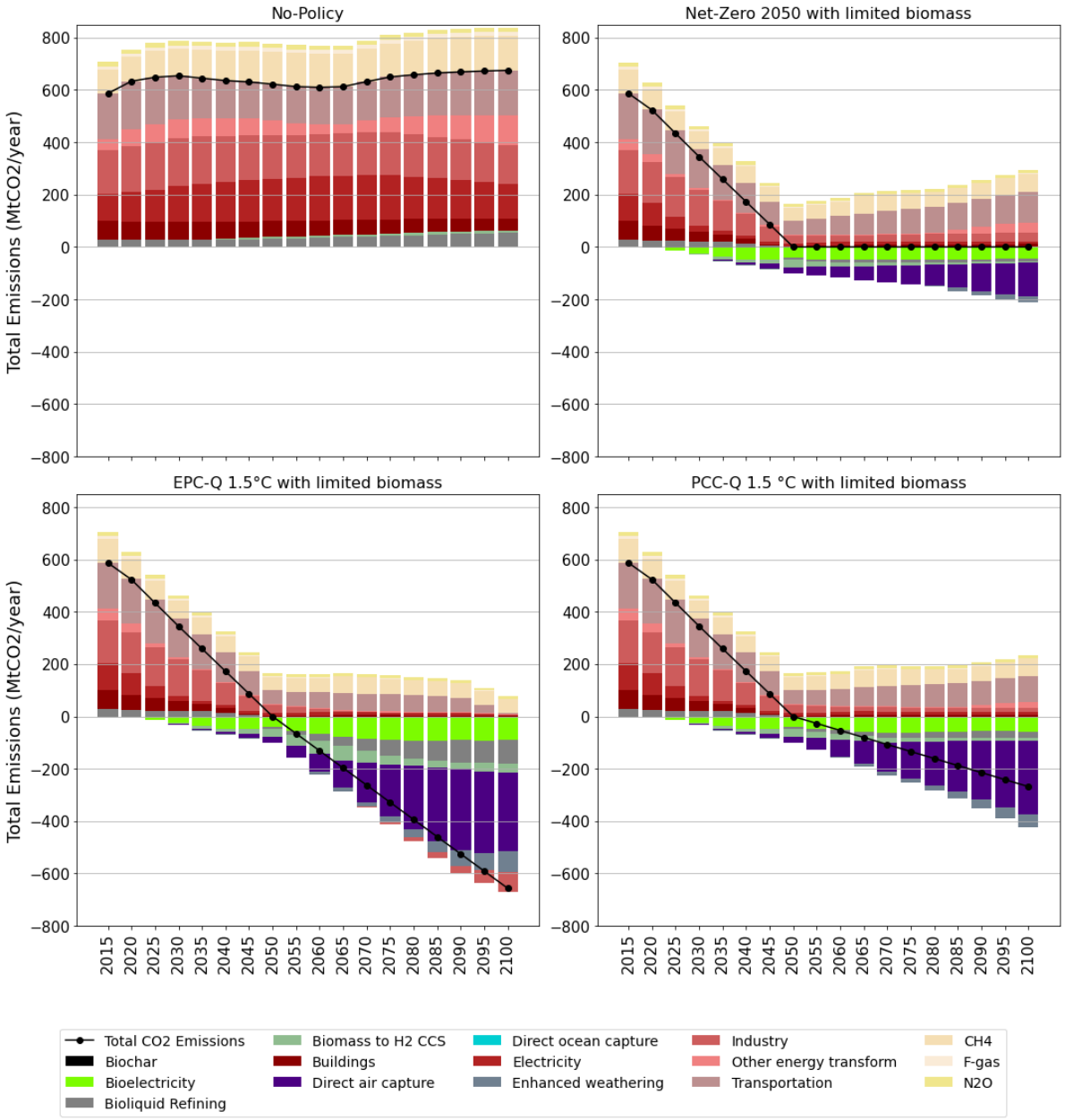
	Removal fraction		
	2020	2050	2095
Refining			
Coal to liquids Phase 1	82%	82%	82%
Coal to liquids Phase 2	98%	98%	98%
Electricity			
Coal	91%	93%	94%
Gas	91%	93%	94%
Oil	91%	93%	94%
Biomass	91%	93%	94%
Hydrogen			
Coal	90%	90%	90%
Gas	90%	90%	90%
Biomass	90%	90%	90%
Cement	90%	90%	90%

Sectoral CO2 emissions and removal plots for scenarios used in the sensitivity analysis

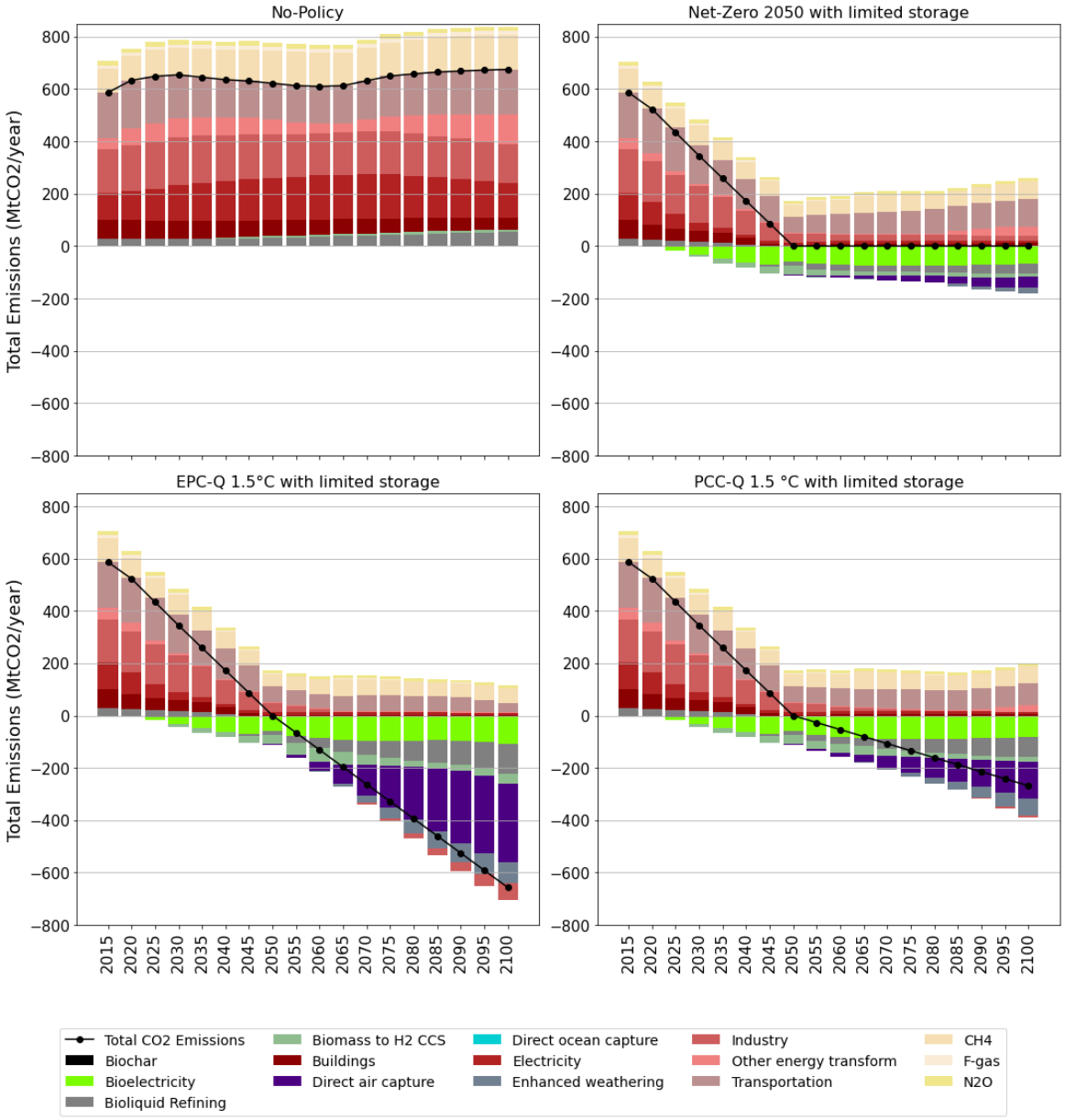
In Figure 3-5 and Figure 3-7 of the paper's main text, sectoral emissions and removals are presented solely for the year 2100. In this section, we provide the results of all sensitivity analysis scenarios for each of the simulated years.



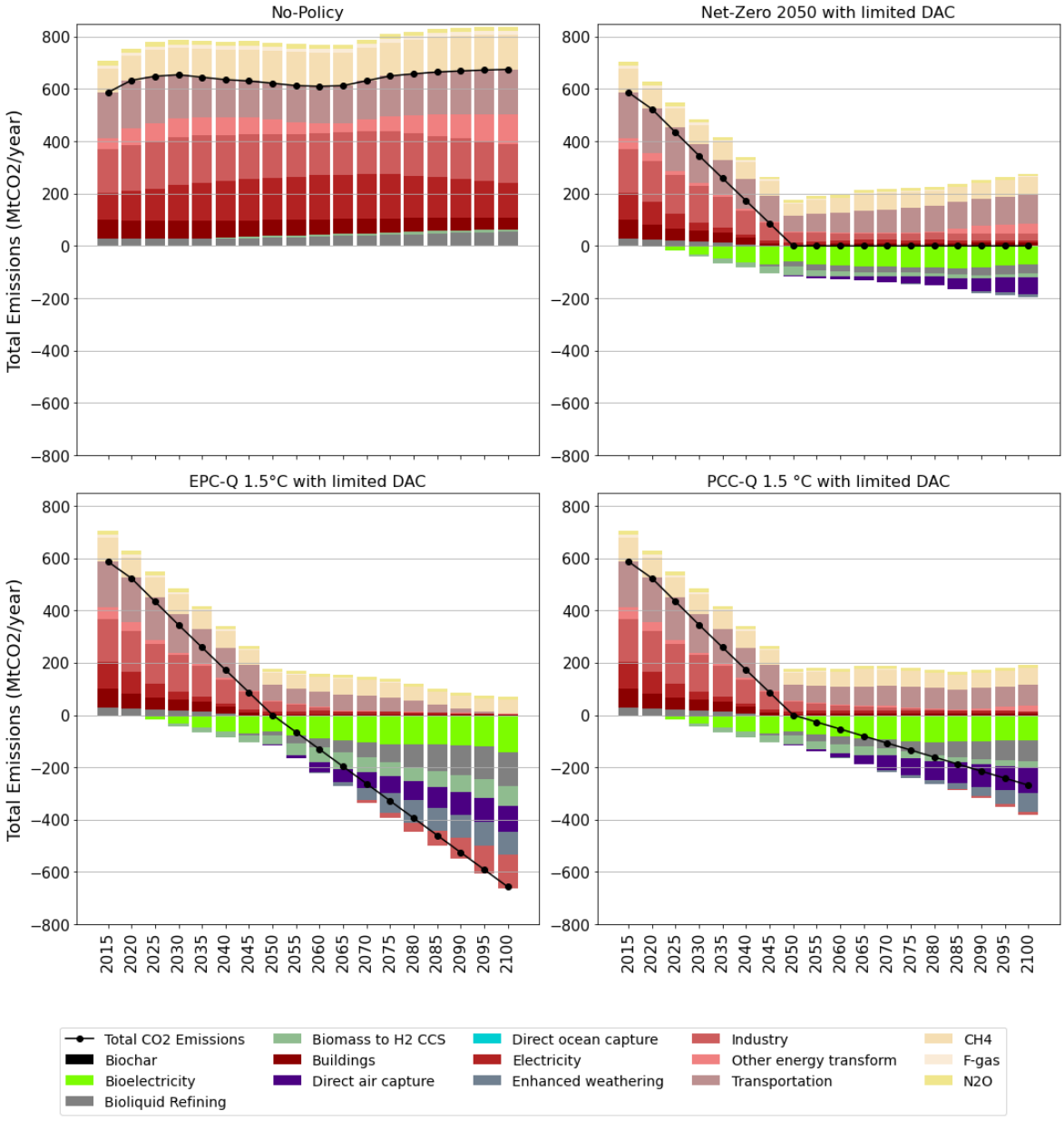
Supplementary Figure 3. Total annual CO_2 emissions/removals by sector for scenarios in which the import of biomass is permitted



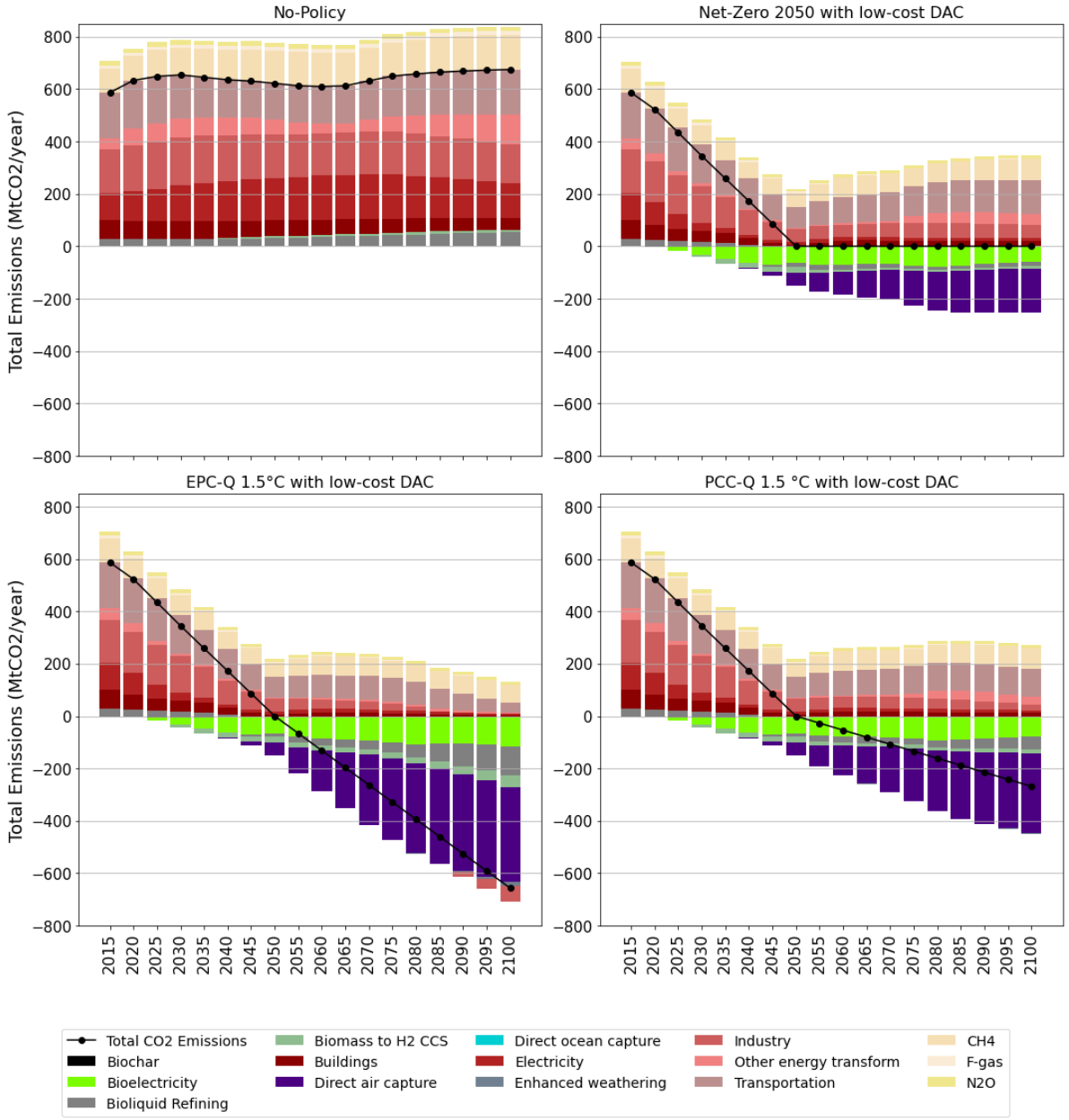
Supplementary Figure 4. Total annual CO_2 emissions/removals by sector in biomass-limited scenarios



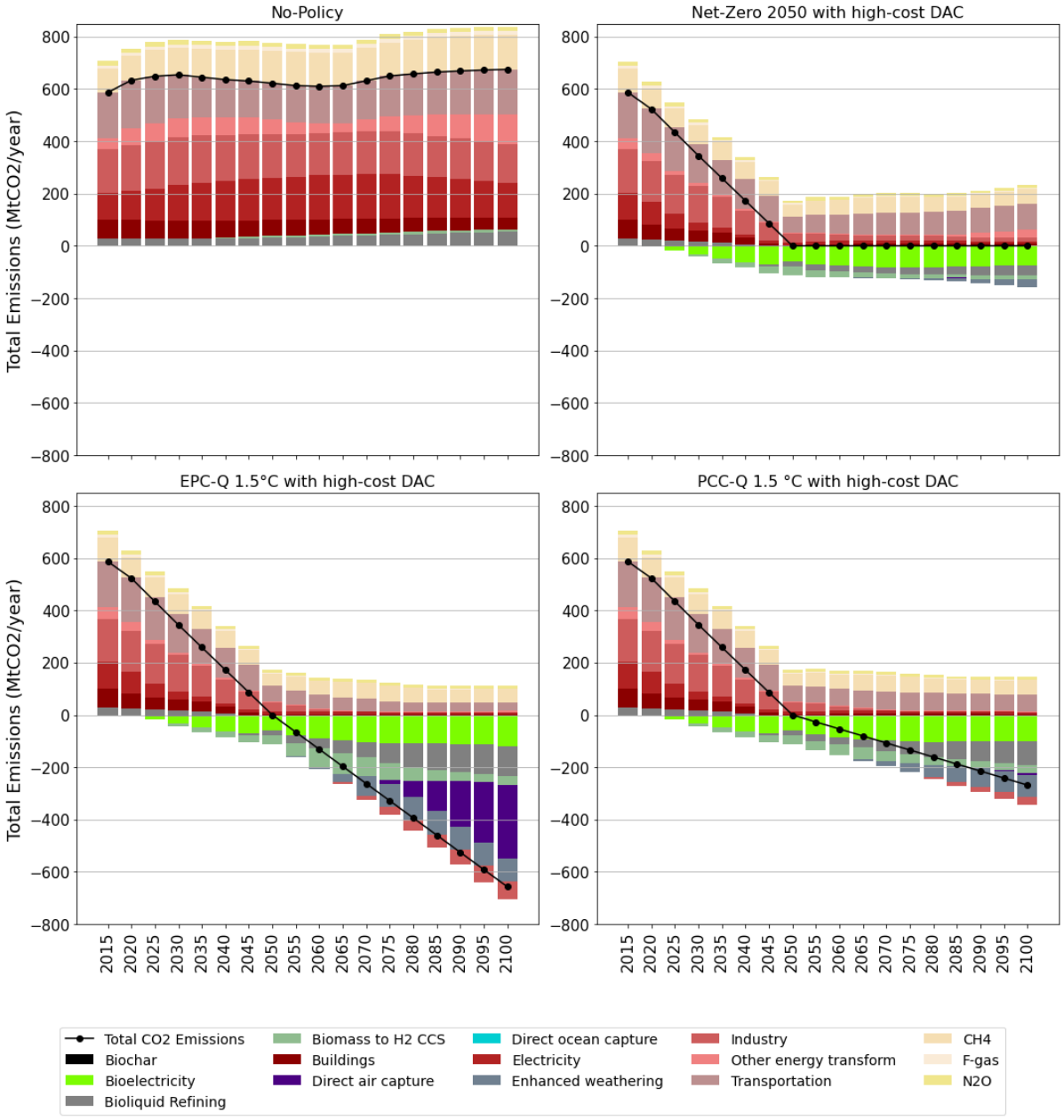
Supplementary Figure 5. Total annual CO_2 emissions/removals by sector in limited carbon storage scenarios



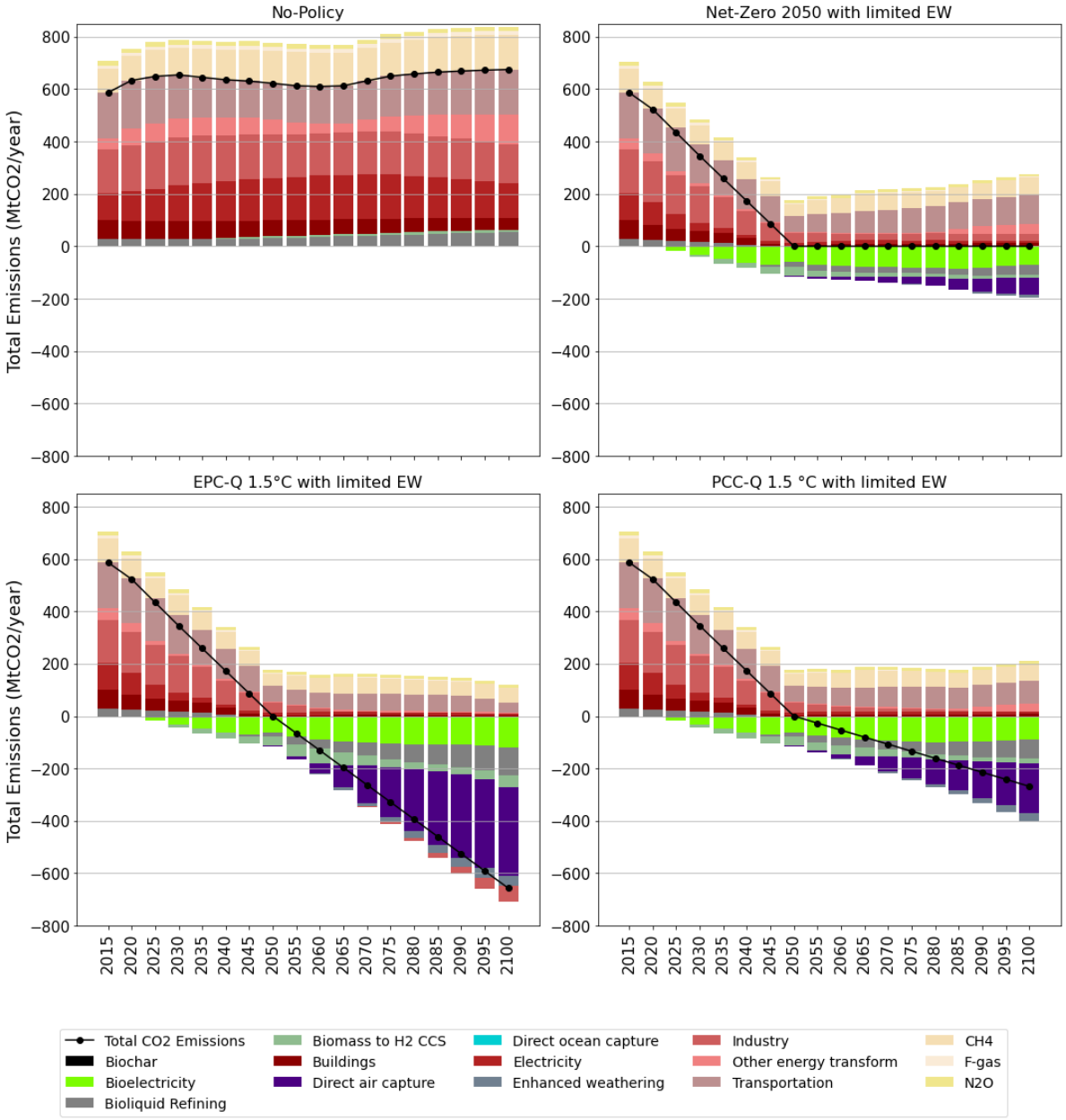
Supplementary Figure 6. Total annual CO_2 emissions/removals by sector in scenarios with limited DAC availability



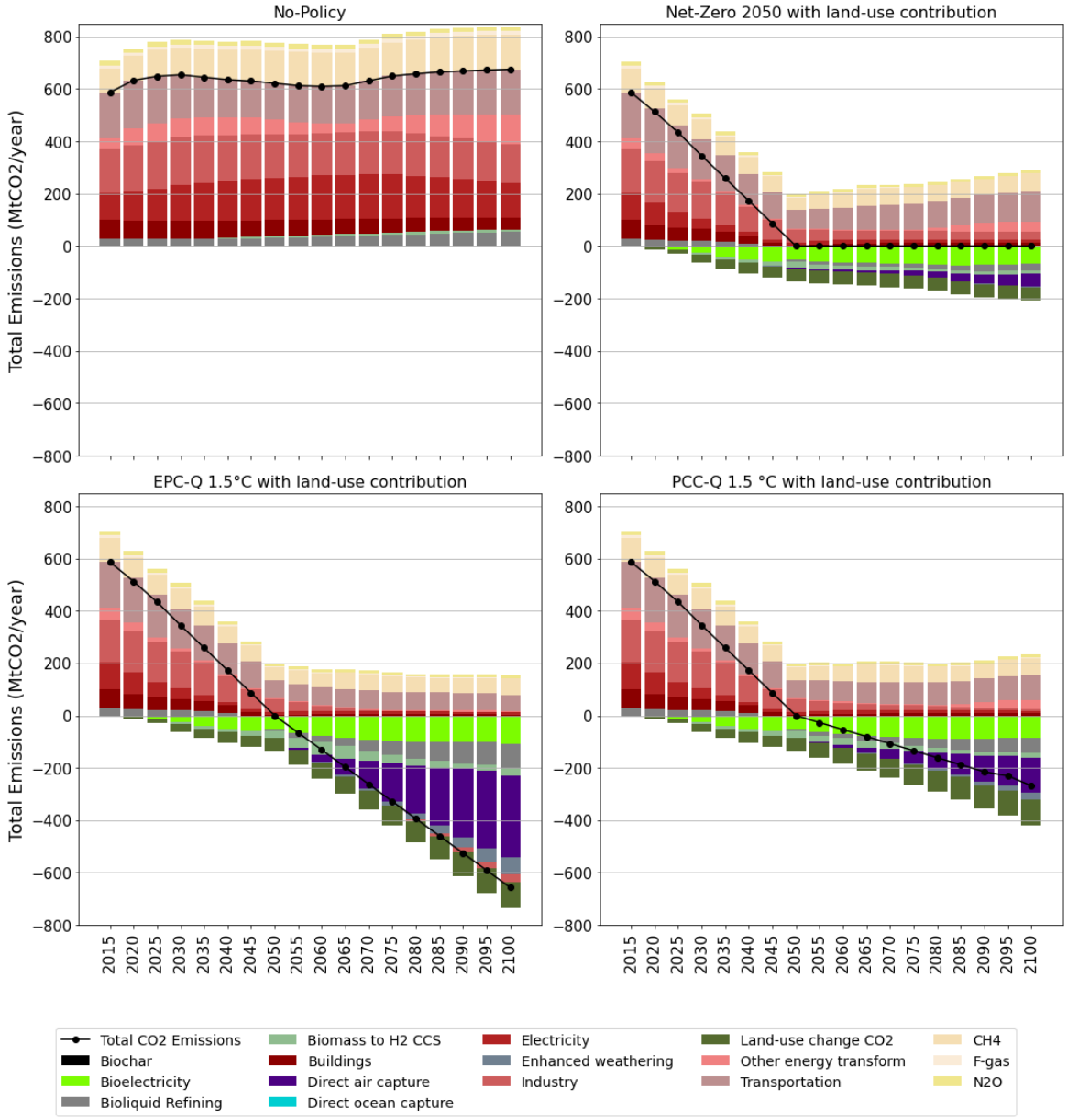
Supplementary Figure 7. Total annual CO_2 emissions/removals by sector in scenarios with low-cost DAC



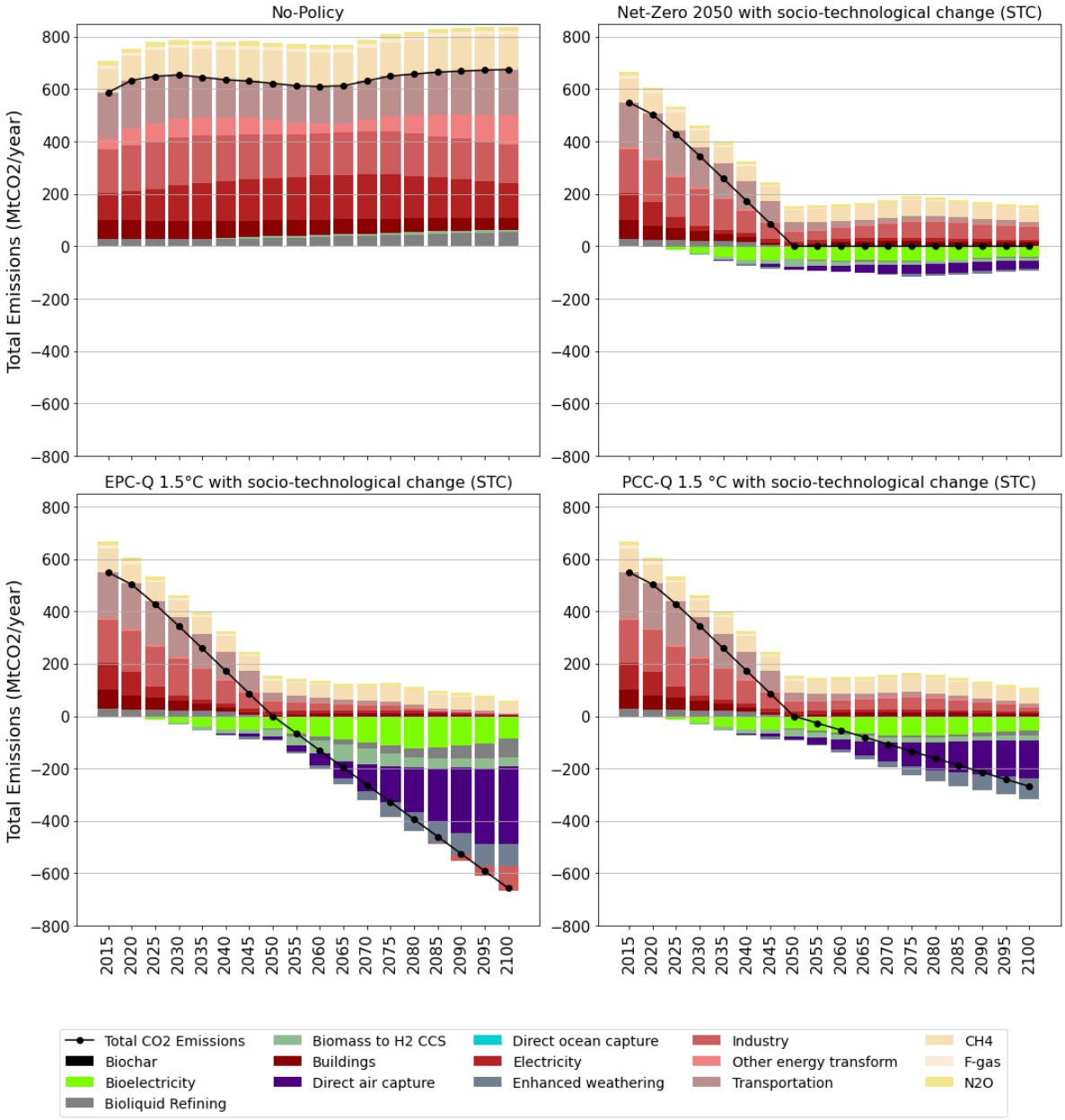
Supplementary Figure 8. Total annual CO_2 emissions/removals by sector in scenarios with high-cost DAC



Supplementary Figure 9. Total annual CO_2 emissions/removals by sector in scenarios with limited enhanced weathering (EW)



Supplementary Figure 10. Total annual CO_2 emissions/removals by sector in scenarios with land-based carbon removal



Supplementary Figure 11. Total annual CO_2 emissions/removals by sector in socio-technological change (STC) scenarios

Classification of historically adopted technologies in Canada

In section Figure 3-6 of the paper ("Growth Rates of CDR vs. Historical Technology Adoption in Canada: Uncertainties and Challenges"), we discussed that we classified historically adopted technologies in Canada, with data collected from the HATCH dataset (Nemet et al., 2023), into two main categories: "Chemical & Material Production" and "Energy." Supplementary Table 2 illustrates how each of these technologies was mapped to these categories.

Supplementary Table 2. Classification of historically adopted technologies.

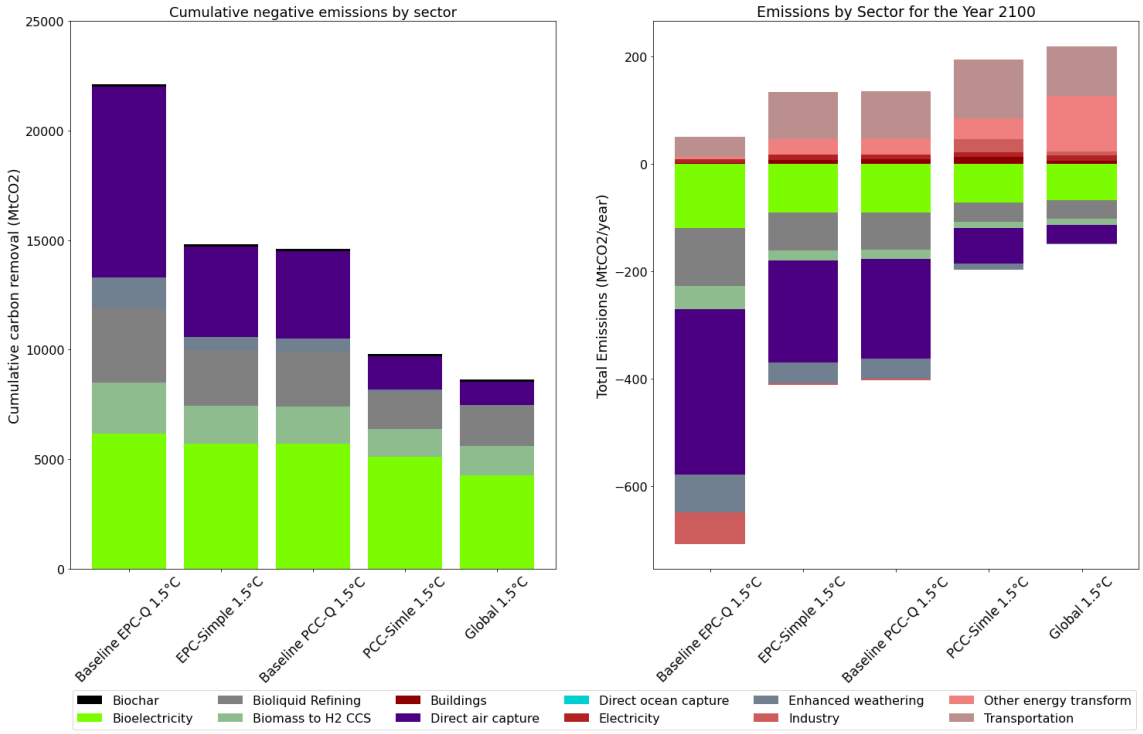
Technology	Category
Ammonia Synthesis	Chemical & Material Production
Hydrochloric Acid	Chemical & Material Production
Nickel Production	Chemical & Material Production
Nitric Acid	Chemical & Material Production
Nitrogen Fertilizer	Chemical & Material Production
Phosphate Fertilizer	Chemical & Material Production
Potash Fertilizer	Chemical & Material Production
Sulphuric Acid	Chemical & Material Production
Synthetic Filaments	Chemical & Material Production
Zinc	Chemical & Material Production
All Biofuels	Energy
Coal Production	Energy
Crude Oil	Energy
Electricity	Energy
Hydroelectricity	Energy
Natural Gas Production	Energy
Nuclear Energy	Energy
Oil Production	Energy
Oil Refining Capacity	Energy
Renewable Power	Energy

B2. From Least-Cost Pathways to Stringent Equity-Based Burden-Sharing Principle

Global IAMs have faced criticism for overlooking equity principles in favor of cost-effective policy pathways. Concerning CDR, various studies have identified inconsistencies between the deployment of CDR by IAMs and the deployment deemed appropriate by different burden-sharing principles (Fyson et al., 2020; Lee et al., 2021; Yuwono et al., 2023). In this section, first, we compare the results of a global RCB aligned with the 1.5°C target as a constraint to the findings of our national RCBs, which involves allocating the NRCB based on equity principles and establishing constraints for GCAM accordingly. The global RCB does not apply equity principles, as it only tells us the amount of CO_2 emissions that the whole world can still emit to achieve a temperature target (here 1.5 °C), thus the difference between the national and global RCB provides a measure of the distributive consequences of equity. Supplementary Fig. 12 reveals that the total cumulative negative emissions from CDR methods for Canada in the global approach are significantly lower than in scenarios based on equity principles (70% and 50% relative to EPC-Q and PCC-Q 1.5°C scenarios, respectively). Moreover, in addition to the lower CDR burdens for Canada in the global scenario, Canadian residual emissions in 2100 will increase from 50 and 134 $MtCO_2$ in the EPC-Q and PCC-Q 1.5°C scenarios to 219 $MtCO_2$ in the global scenario. Given that the global budget for this temperature target remains unchanged from what was applied in the EPC-Q and PCC-Q scenarios, although it was distributed among countries, the disparity of residual and negative emissions indicates that the burden—represented by the difference between equity-based targets and a singular global target—is offset by other regions globally. This is also consistent with the results from previous studies (Fyson et al., 2020; Jones, 2023).

Focusing on the EPC-Simple and PCC-Simple scenarios, these differ from their qualified counterparts (EPC-Q and PCC-Q) by excluding considerations of historical emissions, national capacity, and the benefits accrued by countries from their past emissions. The PCC-Simple scenario, in particular, operates akin to a grandfathering approach, where emissions are allocated based on current or historical levels rather than equity-adjusted criteria. This approach has been critiqued by multiple studies (van den Berg et al., 2020) for perpetuating inequalities and overlooking the moral responsibility of high-emitting nations. As Supplementary Fig. 12 shows, the PCC-Simple scenario, which closely resembles a net-zero scenario where Canada achieves net-zero emissions and maintains it through the rest of the century, results in the lowest CDR burden for Canada. This reflects a more lenient allocation that benefits high emitters by preserving current emissions distributions without accounting for historical responsibility or capacity to act. In contrast, the equity-based PCC-Q scenario assigns a much

larger share of CDR deployment to Canada, reflecting a more equitable approach. Similarly, the EPC-Simple scenario results in a reduced CDR requirement compared to EPC-Q. Both EPC-Simple and PCC-Simple omit important fairness considerations, assigning fewer obligations to Canada, which underscores the potential risks of adopting simplified burden-sharing mechanisms that fail to fully incorporate equity principles.



Supplementary Figure 12. A comparison of Canadian cumulative deployment of novel carbon dioxide removal methods (left column) and positive and negative emissions in 2100 (right column) between a global 1.5 ˚C scenario and other burden-sharing principles.

B3: An example of applying equity-based constraints to GCAM scenarios

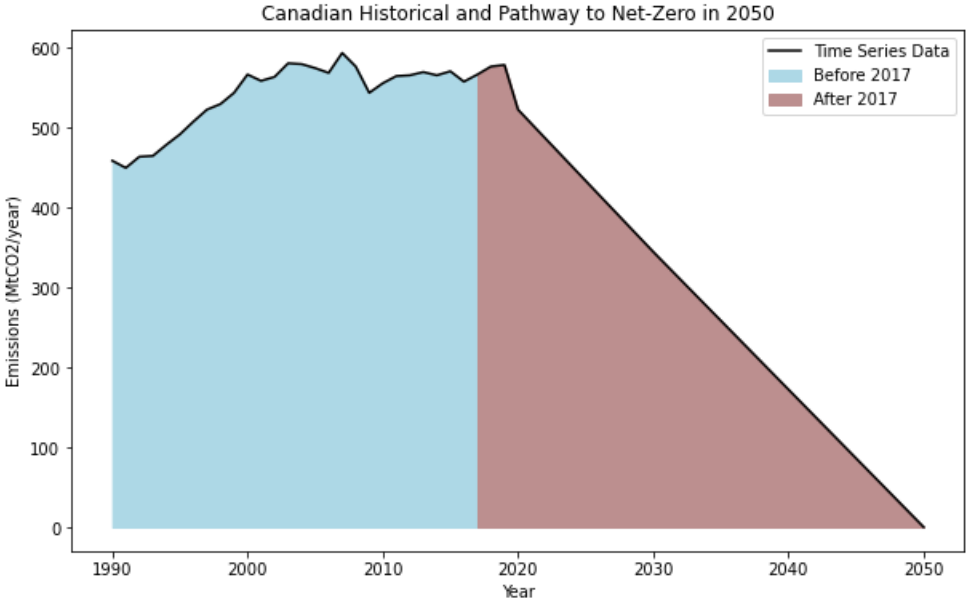
Step 1. Calculating the national remaining carbon budget (NRCB) from a start year

The first step is to calculate the National Remaining Carbon Budgets (NRCBs) for countries based on specific burden-sharing principles, which are derived from different schools of thought and equity dimensions. Several studies have assessed NRCB calculations using various approaches, with two comprehensive examples being Williges et al. (2022) and van den Berg et al. (2020). In this study, we use Canada's NRCB estimates based on the equity principles EPC-Q and PCC-Q from Williges et al. (2022), as the data is openly available and the underlying assumptions are considered reasonable (van

den Berg et al., 2020; Williges et al., 2022). For a 1.5°C target, the EPC-Q and PCC-Q NRCBs for Canada are -6.92 and 2.8 Gt of CO_2 emissions starting from 2017, respectively. The negative value for the EPC-Q approach indicates that Canada has already exceeded the emissions it was allocated under this particular burden-sharing framework.

Step 2. Calculating the emissions in the pathways toward net zero

In this step, we aim to identify the emissions reduction pathway Canada is pursuing based on its short-term and long-term targets. Canada has committed to reducing its emissions by 40-45% by 2030 and achieving net-zero emissions by 2050. Assuming a linear reduction toward both of these targets, we calculated the corresponding emissions trajectory. Supplementary Fig. 13 illustrates this pathway, showing that Canada would emit approximately 9.5 Gt of CO_2 under a linear reduction scenario between the targets.



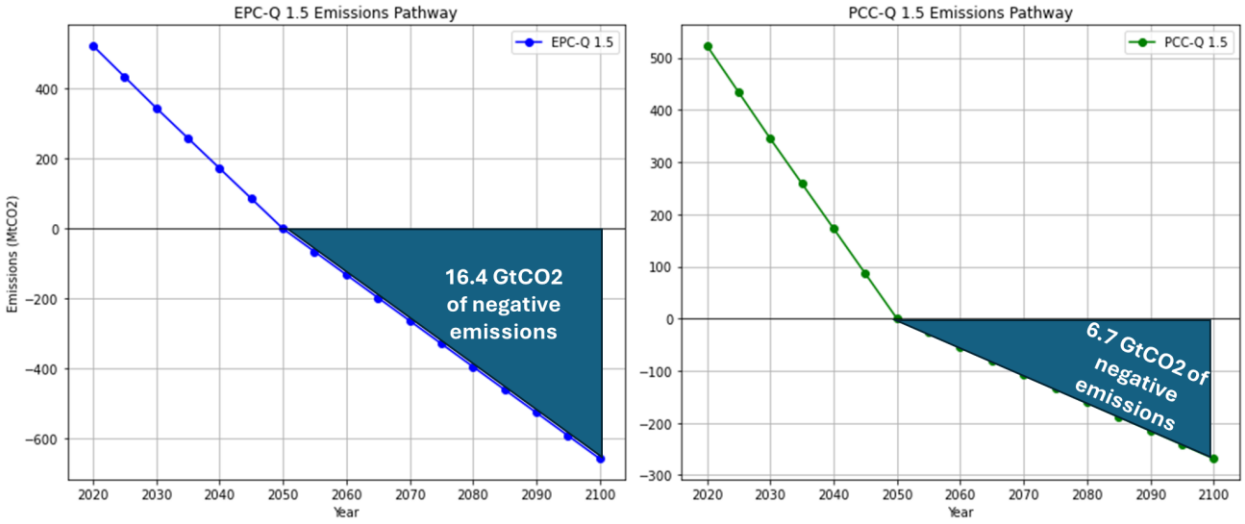
Supplementary Figure 13. Canadian historical and net-zero pathway

Step 3. Finding the post-net-zero carbon budgets/debts

In Step 1, we determined that for a 1.5°C target, the EPC-Q and PCC-Q National Residual Carbon Budgets (NRCBs) for Canada are -6.92 and 2.8 Gt of CO_2 emissions, respectively, starting from 2017. In Step 2, we estimated that Canada would emit approximately 9.5 Gt of CO_2 from 2017 to 2050. Subtracting these emissions from the NRCBs, Canada would accumulate a carbon debt of 16.4 $GtCO_2$ (-6.92 - 9.5) under the EPC-Q approach and 6.7 $GtCO_2$ (2.8 - 9.5) under the PCC-Q approach by 2050.

Step 4. Setting the post-net-zero GCAM constraints

In this step, we explore potential post-net-zero pathways for Canada to address its carbon debt under different scenarios. By assuming a linear increase in the stringency of negative emissions targets, we calculate the corresponding pathways. Supplementary Fig. 14 illustrates these pathways for the EPC-Q and PCC-Q 1.5°C scenarios, where the area under each curve represents the carbon debt to be repaid in each scenario.



Supplementary Figure 14. Post-net-zero negative emissions pathways

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Appendix C
Supplementary Information of Chapter 4

Motlaghzadeh, K., & Schweizer, V. (2025). The future of direct air capture in Canada: A systematic scenario-based exploration of barriers and possibilities. Manuscript in-preparation to be submitted for publication, Environmental Innovation and Societal Transitions.

1. Definitions of descriptors and their variants

Below are the definitions of the descriptors used in the Cross-Impact Balances (CIB) analysis for Direct Air Capture (DAC).

Supply of Low-Carbon Electricity Inputs

DAC requires substantial amounts of both electrical and thermal energy to operate. If this energy is supplied by fossil fuels, it can significantly reduce the net carbon captured (Barahimi et al., 2023; Erans et al., 2022; Motlaghzadeh et al., 2023). This descriptor focuses on the availability of low-carbon energy sources, such as hydro, wind, solar, and nuclear, to power DAC systems. Accessibility to these energy sources is influenced by the development of both generation capacity and transmission infrastructure. Future electricity demand in Canada is expected to rise, driven by factors such as economic growth, energy efficiency improvements, and the electrification of various industries. In 2022, Canada generated approximately 527 TWh of electricity from low-carbon sources(Canada Energy Regulator, 2023). The following variants illustrate different growth scenarios for low-carbon electricity generation (also shown in Figure 1):

- Low growth: Generation increases at a historical rate of 1% per year, reaching around 1000 TWh by 2075.
- Medium growth: Generation grows at a rate between 1–3% per year, achieving between 1000 and 2500 TWh by 2075.
- High growth: Ambitious growth exceeding 3% per year, surpassing 2500 TWh by 2075.

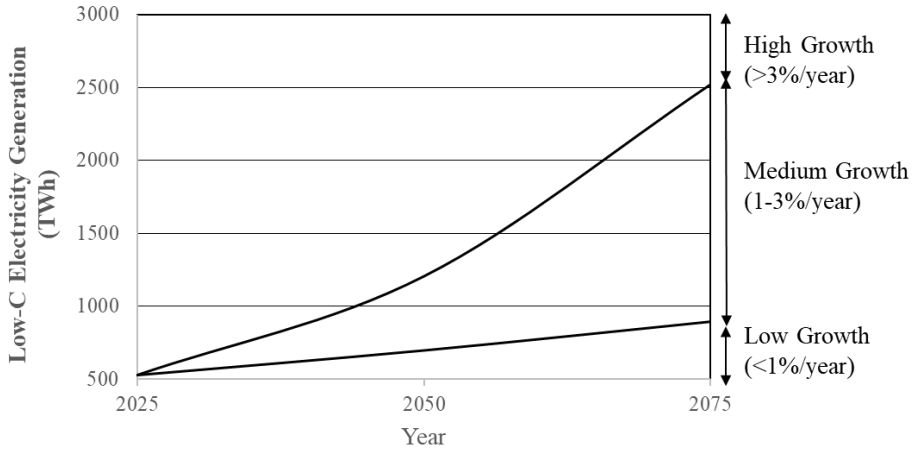

Figure 1. Different variants of the descriptor "Supply of Low-Carbon Electricity Inputs"

Usable Pore Space

Usable pore space refers to the availability and accessibility of the geological storage space (onshore and offshore) for carbon sequestration. Examples of pore space can include but are not limited to basalt formations, oil and gas reservoirs and saline formations (Bashir et al., 2024). Development of storage hubs (currently driven by carbon capture and storage from point sources of emissions such as heavy industries) may streamline costs and infrastructure required to access pore space. Different jurisdictions within Canada may regulate pore space ownership and access differently. For example, Alberta has enacted legislation that vests ownership of all underground pore space in the provincial Crown. Other provinces or offshore areas may have less defined implicit legislation, such as through land, mining, or oil and gas-related Acts. Access to the pore space for DAC may be impacted by regulatory requirements and associated costs, competing users (such as CCS), and available transportation of captured CO_2 (Cortinovis et al., 2024) Recent estimates of onshore storage potential in Canada totals 5860 $GtCO_2$ but current estimates of developed pore space are 27 million tonnes by 2030. The Canadian government has committed to an increase in usable pore from 3 to 15 $MtCO_2$/year. Figure 2 presents different variants for this descriptor which include:

- Low growth: Storage capacity increases by 3 $MtCO_2$/year, reaching 100 $MtCO_2$/year by 2075.

- Medium growth: Storage capacity grows at a rate of 3–15 $MtCO_2$/year, reaching between 100 and 400 $MtCO_2$/year by 2075.
- High growth: Storage capacity grows beyond 15 $MtCO_2$/year and surpasses 400 $MtCO_2$/year by 2075.

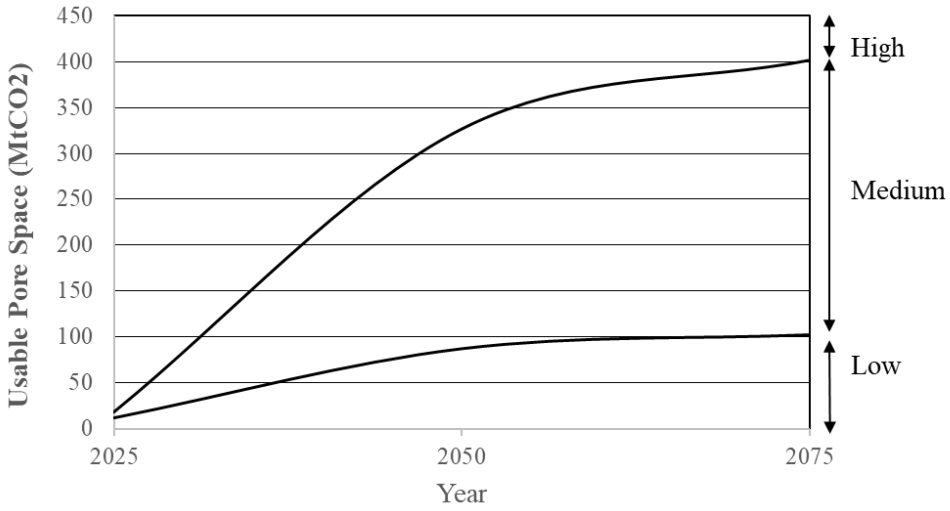

Figure 2. Different variants of the descriptor "Usable Pore Space"

Availability of Other DAC Inputs

Other DAC inputs refers to any inputs to the system other than electricity. They are most notably materials, fuels, heat, and water to run the DAC system, which may eventually also encompass inputs to a CO_2 utilization process if it is combined with the DAC process.

Materials input represents materials of fabrication for the DAC process, which also includes sorbents (in particular for solid sorbent). The sustainability of DAC will depend on the use of affordable, stable, and selective sorbents with a shortage-free supply chain (Chatterjee & Huang, 2020).

Fuel input is primarily relevant for liquid sorbent to provide heat to the calciner unless high-grade heat (at least 700°C) is available (Erans et al., 2022).

Heat input includes mostly the availability of waste heat (e.g., 80 to 200°C) for solid sorbent technology(Barahimi et al., 2023). It is understood that heat can also be generated either through fuel

combustion or via electricity, in which case meeting heat requirements would fall under fuel availability or low-carbon electricity generation.

Water input is more relevant to liquid sorbent-based DAC technologies but can become a major input when DAC is combined with a CO_2 utilization process to produce fuels and chemicals (Barahimi et al., 2023).

- Low availability: Non-electricity critical input shortages constrain DAC feasibility.
- High availability: Non-electricity critical inputs are abundant, supporting DAC deployment.

Carbon Pricing

The carbon market assigns a monetary value to reduce or remove greenhouse gas emissions, creating a financial incentive for technologies that capture and store CO_2 (Bednar et al., 2023). The carbon market can provide a crucial revenue stream for DAC technologies. As the price of carbon credits rises, the economic feasibility of DAC operations improves, making it more attractive for investors and operators(Sovacool et al., 2022). Furthermore, a robust carbon market can stimulate demand for carbon offsets from industries and sectors that find it challenging to reduce their emissions directly. In turn, this demand can drive the expansion of DAC installations. Additionally, as governments and international bodies tighten climate regulations and set more ambitious carbon neutrality targets, the value and importance of the carbon market are likely to grow. Alternatively, governments may repeal carbon taxes. The projected carbon tax in Canada by 2025 is \$95/tonCO_2(Environment and Climate Change Canada, 2021), serving as the baseline for all three variants outlined below. These variants illustrate different rates of increase in carbon pricing (also shown in Figure 3):

- Low pricing: The carbon tax increases no more than \$10/ton per year up to 2050. The yearly increase is reduced in half after 2050 to \$5/ton CO_2 up to 2075.
- Medium pricing: The carbon tax increases \$10-30/ton per year up to 2050. The yearly increase is reduced in half after 2050 to \$15/ton CO_2 up to 2075. Currently the carbon tax is scheduled to increase \$15/ton per year.
- High pricing: The carbon tax increases \$30/ton per year up to 2050. The yearly increase is reduced in half after 2050 to \$15/ton CO_2 up to 2075.

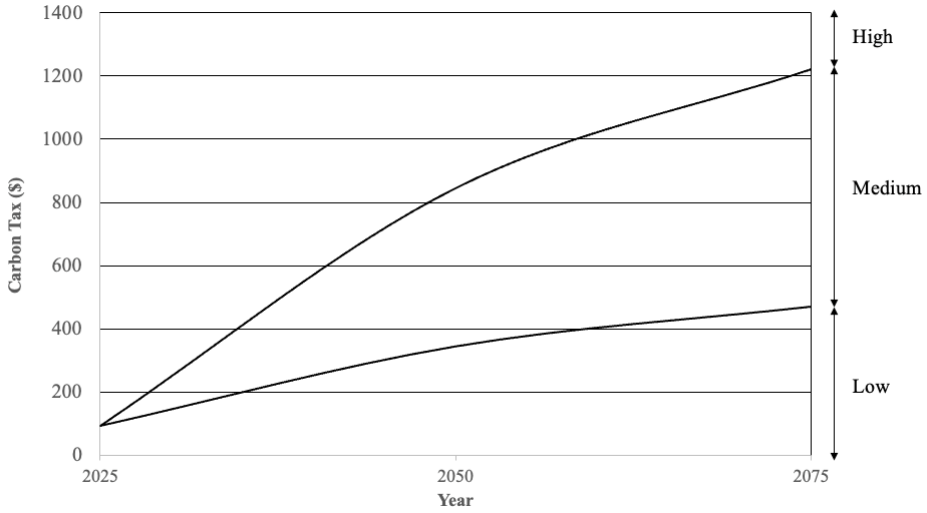

Figure 3. Different variants of the descriptor "Carbon Pricing"

Cost of DAC

DAC installations' high initial capital costs and operational expenses are currently a barrier to their widespread adoption (Motlaghzadeh et al., 2023). However, as the urgency to address climate change intensifies, governments and private entities' investment in research and development can lead to technological advancements and cost reductions (Young et al., 2022). As investments in research and development increase, breakthroughs in related fields, such as advanced materials science or renewable energy integration, can further enhance the efficiency and affordability of DAC. The historical trajectories of other clean technologies, like solar photovoltaics (Green, 2019) and wind turbines, showcase how learning rates can affect costs and spur adoption. Three cost trajectories for DAC are considered based on recent literature (Keith et al., 2018; Socolow et al., 2011; Young et al., 2023) that are also shown in Figure 4.

- Low cost: In 2025, the levelized cost per ton captured is \$232/ton CO_2. The costs are assumed to decline at 4% per year through 2075.
- Medium cost: In 2025, the levelized cost per ton captured ranges from \$232-\$550/ton CO_2. The costs are assumed to decline at 1.6-4% per year through 2075.
- High cost: The levelized cost per ton captured is \$550/ton CO_2 or greater. The costs are assumed to decline at 1.6%/yr.

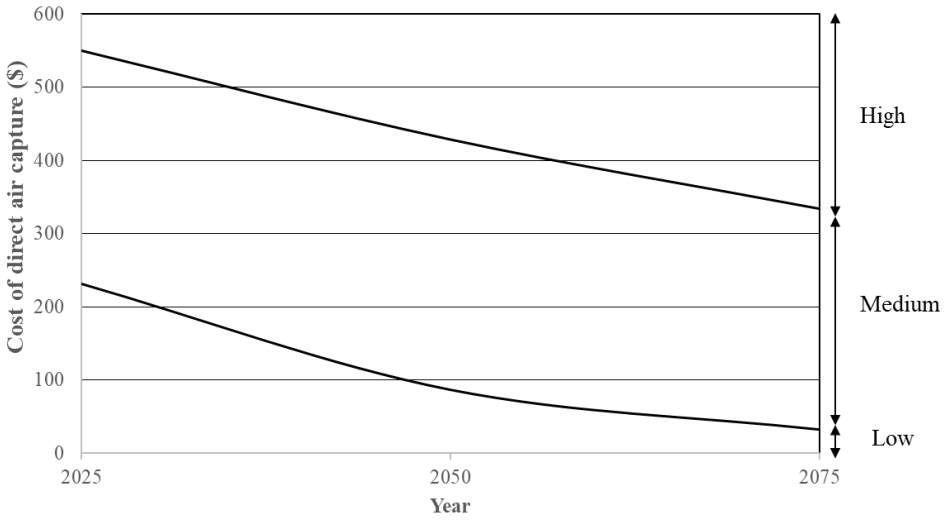

Figure 4. Different variants of the descriptor "Cost of direct air capture"

Market Demand for Products Utilizing Captured CO_2

The potential utilization of CO_2 captured by DAC technologies can significantly influence their deployment and scalability. Utilizing the captured CO_2 for practical applications creates an added value proposition for DAC (Motlaghzadeh et al., 2023). This CO_2 can be converted into a range of products, from synthetic fuels and chemicals to building materials, thereby creating a circular carbon economy. Such utilization pathways can generate additional revenue streams for DAC operations, enhancing their economic viability. Moreover, industries that rely on carbon-intensive processes might find DAC-derived CO_2 as a sustainable feedstock, aligning with their environmental and sustainability goals. The promise of CO_2 utilization also attracts investments and research into improving DAC efficiency and reducing costs. The broader the range and scale of CO_2 utilization opportunities, the more incentivized stakeholders become to deploy and support DAC technology (Brazzola et al., 2024). By transforming a greenhouse gas from a pollutant into a valuable resource, the narrative shifts from mere mitigation to opportunity, accelerating the integration of DAC into national and global climate strategies. The ranges are based on projections of the global CO_2 utilization market in 2100, as estimated by Akimoto et al. (2021) under various scenarios(Akimoto et al., 2021), scaled to 1% to approximate Canada's share of the global carbon market. These ranges are shown in Figure 5 and provided below:

- Low demand: Less than 3 $MtCO_2$/year will be utilized in Canada by 2075.
- Medium demand: 3-5 $MtCO_2$/year and will be utilized in Canada by 2075.
- High demand: More than 5 $MtCO_2$/year will be utilized in Canada by 2075.

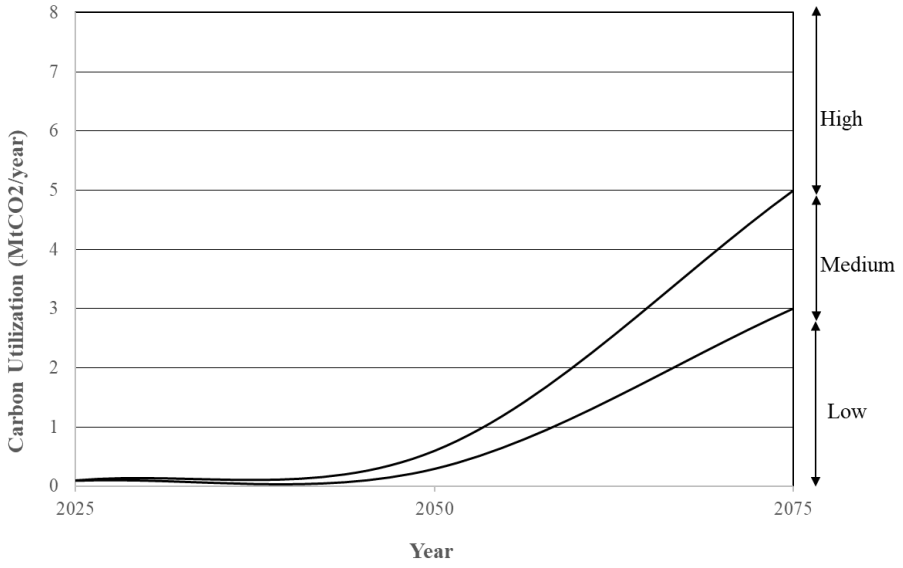

Figure 5. Different variants of the descriptor "Market Demand for Products Utilizing Captured CO2"

National CDR Demand

National demand for CDR can be influenced by various factors, including future societal demand for energy services, energy intensity of the economy, the timing of achieving net-zero emissions, the challenges of mitigating hard-to-abate emissions, the impacts of climate change(Hanna et al., 2021), and the maturity of mechanisms for international carbon credit trading(Lee et al., 2021). Certain factors, either independently or in combination, may induce varying degrees of demand for CDR. Here we provide quantitative benchmarks and describe alternative conditions where Canadian CDR demand could be categorized as Low, Medium, or High. These CDR demand ranges (as shown in Figure 6) are based on a study by Fuhrman et al. (2021) where they explored the role of different CDR methods under different shared socio-economic pathways and temperature targets(Fuhrman et al., 2021).

- Low Demand: By 2075, < 100 $MtCO_2$/year is removed. CDR demand is low because progress towards net-zero emissions by 2050 is achieved primarily through successful emissions reductions.
- Medium Demand: By 2075, 100 – 400 $MtCO_2$/year is removed. CDR demand is substantial. For example, less ambitious emissions reductions may need to be offset to achieve net-zero emissions by 2050. A maturing international CDR market may prompt Canada to explore its economic comparative advantages within it.
- High Demand: By 2075, > 400 $MtCO_2$/year is removed. CDR demand is significant. For example, the net-zero emissions by 2050 goal is delayed until later in the century through extensive CDR efforts. Alternatively, elevated climate change impacts where adaptation measures prove to be less effective may lead countries to deploy CDR as an emergency response. For example, such a trend might necessitate policy discussions that move the goals for net-zero earlier, such as to 2045.

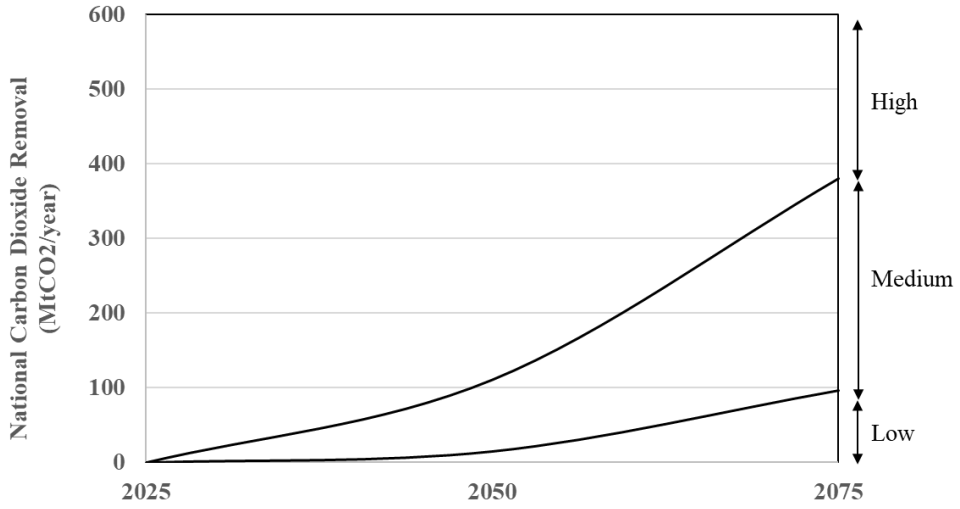

Figure 6. Different variants of the descriptor "National CDR Demand"

Competitiveness of DAC Relative to Other CDR Options

CDR encompasses a variety of methods aimed at extracting CO_2 from the atmosphere. These approaches encompass a broad range of techniques, including DAC, soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), enhanced weathering, ocean-based CDR strategies, and afforestation/reforestation efforts. These methods might vary regarding their costs;

inputs; potential; environmental footprints; co-benefits; permanency of the captured carbon; and measurement, reporting, and verification (MRV) of the captured carbon(Fuss et al., 2018). This descriptor captures how other CDR methods are doing compared to DAC regarding these characteristics. Alternative outcomes may be DAC outcompeted, DAC among equals, or DAC dominance.

- Low competitiveness: DAC compares poorly to other CDR options in Canada.
- Moderate competitiveness: DAC compares equally to other CDR options in Canada
- High competitiveness: DAC compares favourably to other CDR options in Canada

Public Perception of DAC

Public perception of DAC refers to public opinion of DAC. Its systemic influence might be perceived through how DAC is portrayed in journalistic media as well as whether communities oppose or support nearby DAC projects. Currently there is low awareness amongst the general public around DAC, CDR, and what they entail. Studies suggest that residents located near proposed pilot facility sites have varying levels of trust and support in DAC(Satterfield et al., 2023). The perceived local risks and anticipated benefits of the technology are likely to significantly influence local acceptability. Additionally, the extent to which project developers and government partners effectively address moral hazard concerns—such as the potential for CDR to undermine emissions reduction efforts—will play a crucial role in shaping public acceptance(Satterfield et al., 2023). Public acceptance is further influenced by the power of objectors. For example, under Section 35 of the Constitution Act, the government has a duty to consult Indigenous peoples when government activities could infringe on Indigenous treaty rights, which may delay future projects. Given these complexities, it is challenging to predict future trends in public perception using a single metric. Hypothetical trajectories for public perception through 2075 are outlined as follows.

- Oppositional or polarizing (Low public acceptance): Significant opposition to DAC prevents or severely limits DAC deployment.

- Neutral impact overall (Moderate public acceptance): Overall, public perception (or differences in public perception) is not a source of major project delays for DAC deployment.
- Supportive (High public acceptance): Widespread public acceptance of DAC encourages or hastens DAC deployment. For example, DAC may be associated with co-beneficial outcomes such as meeting local community needs, expansion of renewable energy, or embodying circular economy principles.

Policy Coherence and Cooperation

Canada, as a federal state, has both provincial and federal governments with the authority to regulate various aspects of DAC and carbon storage. The extent to which the policy and regulatory environment establishes a coherent framework for DAC development and deployment can significantly impact the cost-effectiveness and scale of carbon removal achieved through DAC. For instance, inconsistent or incompatible policies regarding storage, CO_2 transportation, low-carbon energy sources, and innovation support could hinder DAC development by reducing efficiency or imposing operational constraints. Coherence may also depend on the level of cross-border cooperation with the U.S. on energy, CO_2 transportation, and storage. The levels of coherence and cooperation are categorized as follows.

- Low coherence: Highly fragmented regulatory environment in 2075, where DAC and carbon storage issues are handled differently across provinces; m-jurisdictional cooperation
- Partial coherence: A few jurisdictions cooperate by 2075
- High coherence: A unified or highly integrated regulatory environment by 2075, with high levels of inter-jurisdiction cooperation

2- Experts Attended the Canadian DAC Scenario Workshop

Table 1. Experts who attended the Canadian DAC workshop and consented to share at least part of their information (name, position, and organization).

Full name	Position	Organization
Cameron Roberts	Postdoctoral Researcher	University of Wisconsin Madison
Candice Paton	Vice President	Enhance Energy Inc.
ND	ND	BC Centre for Innovation and Clean Energy
Claudio Adrian Ruiz Torres	Postdoctoral Fellow	University of Toronto
Frank Zeman	Associate Professor	Royal Military College of Canada
James Meadowcroft	Professor	Carleton University
ND	ND	Environment and Climate Change Canada
Kevin Hanna	Associate Professor	University of British Columbia
Kristen Schell	Assistant Professor	Carleton University
Marc Saner	Professor	University of Ottawa
Mohamad Moosavi	Assistant Professor	University of Toronto
Na'im Merchant	Executive Director	Carbon Removal Canada
Nigel Bankes	Professor Emeritus	University of Calgary
Peter Freudenstein	Climate Policy Manager	Climeworks
Robert Walsh	Senior Engineer	Geofirma Engineering Ltd.
Ryan Bourns	Business Strategy Development Manager	Carbon Upcycling Technologies
Sean Wilson	Co-Founder & CEO	TerraFixing Inc.
Sean McCoy	Assistant Professor	University of Calgary
Serge Nadon	Senior Policy Advisor	Office of the Chief Science Advisor of Canada
Simon Langlois-Bertrand	Researcher and analyst, Energy and Climate Policy	Institut de l'énergie Trottier
Tim Bushman	Director of Policy and Research	Carbon Removal Canada

3- CIB Input Matrix

As described in Section 4.2.2 of the main text, the input to the CIB analysis is a cross-impact matrix, developed based on insights from experts in DAC. Table 2 of the SI presents this matrix, where colors indicate both the direction of influence (either promoting or hindering) and the strength of relationships between variables. Essentially, this figure illustrates how the descriptors in different rows influence the target variables in the corresponding columns.

It is important to note that some descriptors are influenced by a relatively higher number of factors within the system, such as the availability of usable pore space, while others, like the availability of low-carbon electricity, are influenced by only a few. However, having fewer direct influences does not imply a lack of significance. Instead, it suggests that the primary factors shaping those descriptors lie beyond the system boundary as defined in this study. For instance, while low-carbon electricity is largely determined by external factors, it exerts a strong influence on many descriptors within our system. In this section, we review the logical relationships governing these influences, following the order in which scenarios appear in Table 4-1 of the main text. It should be noted that all these influences were either directly provided by the expert panelists or interpreted by our research team, based on the explanations offered by the experts.

Supply of Low-Carbon Electricity Inputs (A): The supply of low-carbon electricity is influenced by multiple factors. A high carbon price (D) can incentivize further decarbonization of the electricity grid by discouraging natural gas use. However, given that Canada's grid is already relatively clean, achieving this would require significantly high carbon prices. Experts also suggested that greater CDR demand (G)—where DAC is competitive (H), publicly supported (I), and backed by a nationally coherent policy mechanism (J)—might weakly promote the expansion and availability of low-carbon electricity for this technology. This aligns with proposals for siting DAC in remote regions (Vézina & Brouillette, 2021), where grid expansion is economically inefficient due to low population density and high capital costs. In such cases, DAC deployment could create additional demand for low-carbon electricity, potentially justifying infrastructure investments. However, we consider this perspective applicable only under specific conditions. As a result, we incorporated only a weak influence in our analysis. In our ensemble analysis (Section 4.3.3), we explored an alternative mental model provided by another expert, in which there is no direct influence from DAC competitiveness, public perception, or policy coherence on the availability of low-carbon electricity inputs (see Section 4 of the SI).

Usable Pore Space Availability (B): The availability of usable pore space is shaped by multiple factors. According to one expert, a limited supply of low-carbon electricity (A) may constrain expansion into regions where power and geological storage are not co-located, as carbon sequestration requires energy. Similarly, a high availability of other (non-electricity) DAC inputs (C) could facilitate exploration of more remote storage sites. However, another expert did not perceive such direct influences. To reflect this divergence, our ensemble analysis (Section 4.3.3) includes an alternative mental model in which neither non-electricity DAC inputs nor low-carbon electricity availability directly influence the availability of usable pore space (see Section 4 of the SI). Carbon pricing (D) can also influence pore space availability, with higher prices potentially making marginal storage sites more viable, though this effect is more pronounced at elevated price levels. The cost of DAC (E) further shapes deployment, as lower costs allow for broader geographic expansion. While strong market demand for captured CO_2 (F) could reduce reliance on pore space by promoting CO_2 utilization, the significant gap between projected storage needs and market demand suggests a relatively weak influence. While DAC is not the only technology requiring pore space for CO_2 storage, experts noted that strong public support (I) can facilitate its expansion by reducing opposition and securing social license. Policy coherence around DAC technology (J) also plays a critical role, as well-aligned policies can facilitate the exploration of storage sites and the development of necessary infrastructure.

Availability of Other DAC Inputs (C): The availability of other (non-electricity) DAC inputs, such as materials, infrastructure, and transportation, is primarily influenced by the supply of low-carbon electricity (A), as clean energy is crucial for many DAC-related processes. A lower cost of DAC (E) can also improve input availability by fostering technological learning and economies of scale. High market demand for CO_2 products (F) may encourage the production of key DAC inputs, such as hydrogen for heating and specialized materials for plant construction. However, DAC's competitiveness (H) has a weaker effect on input availability—some experts argued that an uncompetitive DAC industry might struggle to secure essential resources, while others suggested that broader industrial demand would ensure continued supply. Policy coherence (J) is an important driver, as strong policies can accelerate research and development, improving access to DAC inputs.

Carbon Pricing (D): Carbon pricing is influenced by multiple interacting factors. Limited usable pore space (B) may weaken political support for high carbon prices, as fewer storage options could reduce the effectiveness of a price-driven approach. However, ample pore space does not necessarily lead to higher carbon prices. Some experts suggested that by 2075, carbon pricing could

help sustain CDR demand if deployment is constrained by high DAC costs (E), as higher DAC costs may require stronger price signals to ensure viability. A robust market for CO_2 utilization (F) could slightly ease pressure on carbon pricing by providing an alternative revenue stream for DAC. Additionally, some experts argued that high CDR demand (G) would necessitate strong carbon pricing to signal investment and incentivize CDR projects. There were two distinct mental models regarding the influence of policy coherence (J) on carbon pricing (D), and due to the lack of consensus among experts, this relationship was not included in our baseline CIB input matrix. However, both alternatives were explored in the ensemble analysis (Section 4.3.3). In the first alternative, a highly coordinated policy approach around DAC could lead to the use of high carbon prices to support its deployment. In the second, low policy coherence might necessitate higher carbon prices to compensate for the lack of strategic alignment in achieving emissions reductions or negative emissions (see Section 4 of the SI).

Cost of DAC (E): The cost of DAC is influenced by several technological and economic factors. The availability of low-carbon electricity (A) is a critical determinant, as clean power constitutes a major operational cost for DAC facilities. Greater usable pore space (B) can reduce costs by allowing for better energy integration and reducing storage constraints. Material shortages and infrastructure bottlenecks may drive costs upward, linking DAC expenses to the availability of inputs (C). High national demand for CDR (G) can help lower costs through economies of scale, as larger deployment fosters technological learning. Similarly, DAC's competitiveness (H) is self-reinforcing—greater competitiveness can drive cost reductions over time. Public perception (I) also plays a role, as greater societal acceptance can reduce legal and administrative barriers, thereby lowering costs. Finally, policy coherence (J) can help drive down DAC costs by ensuring stable regulations, infrastructure investments, and research incentives.

Market Demand for Products Utilizing Captured CO_2 (F): Market demand for captured CO_2 is shaped by multiple factors. Limited usable pore space (B) may encourage CO_2 utilization in commercial applications instead of storage, though this effect is relatively weak. High carbon pricing (D) can support CO_2 market development by incentivizing circular economy practices and industrial tipping points. Lower DAC costs (E) can also stimulate demand by making captured CO_2 more affordable for industrial applications. Additionally, policy coherence (J) can play a significant role by providing subsidies and regulatory incentives that support CO_2 utilization.

National Demand for CDR (G): While the national demand for CDR in Canada is primarily shaped by factors outside our system boundary—such as the pace of decarbonization, which determines residual emissions and thus the amount of CDR needed—other external drivers include potential post–net-zero CDR obligations, which could further increase long-term demand. However, our experts also pointed to several internal system descriptors that influence national CDR demand. For instance, carbon pricing (D) plays a significant role: higher carbon prices improve the cost-competitiveness of CDR methods, encouraging their uptake. Technological feasibility and costs are equally important—greater DAC competitiveness (H) and lower DAC costs (E) can further boost demand, especially given DAC's scalability. CO_2 utilization (F) may also contribute, although its influence is relatively weak due to the limited size of the utilization market. Finally, public perception (I) can shape deployment trajectories, as broad social acceptance of DAC and other CDR methods could accelerate national adoption

DAC Competitiveness (H): CDR methods differ in terms of cost, input requirements, potential scale, environmental footprint, co-benefits, carbon permanence, and the robustness of measurement, reporting, and verification (MRV) systems. This descriptor reflects how DAC compares to other CDR methods across these dimensions. The competitiveness of DAC is shaped by several interrelated factors. A limited supply of low-carbon electricity (A) undermines DAC's viability, as it is among the most energy-intensive CDR options. Similarly, constraints on usable pore space (B)—especially if there is competition with other applications like carbon capture and storage—can disadvantage DAC relative to storage-independent methods such as enhanced rock weathering or biochar. A lack of access to critical DAC inputs (C), including sorbents, water, and essential materials, further limits its competitiveness. Conversely, lower DAC costs (E) significantly enhance its market position and may trigger a positive feedback loop where broader deployment leads to further cost reductions. Public perception (I) also matters—greater societal acceptance of DAC can improve its standing compared to nature-based solutions like afforestation. Finally, policy coherence (J) is essential: streamlined regulations and strong interprovincial coordination can facilitate deployment and strengthen DAC's relative competitiveness.

Public Perception of DAC (I): The public perception of DAC is influenced by various economic and political factors. The cost of DAC (E) directly affects public acceptance, as high costs may lead to resistance from taxpayers and policymakers. A strong market for CO_2 utilization (F) may improve public perception by framing DAC as an industrial opportunity rather than solely a sequestration technology. However, increased competition from other CDR methods (H) may lead to

skepticism about DAC's role in the overall climate strategy. Policy coherence (J) and public perception are mutually reinforcing—strong policy support can enhance public trust, while positive public perception can drive consistent policymaking.

Policy Coherence and Cooperation (J): Policy coherence and inter-provincial cooperation are shaped by several interacting factors. According to one expert, a high carbon price (D) can enhance political alignment by improving DAC's economic viability and fostering a strong lobbying force in its favor—an influence reflected in our baseline CIB input matrix. However, another expert did not see a direct impact of carbon pricing on policy coherence, a perspective explored in our ensemble analysis. Market demand for CO_2 products (F) may may lessen the need for interprovincial cooperation, as industries could rely on localized CO_2 utilization options, thereby reducing the necessity for government oversight. A low or moderate national demand for CDR (G) can foster fragmented or only partially coherent policies around DAC. In contrast, high CDR demand (G3) may exert different influences depending on its underlying drivers. If such demand reflects shortcomings in broader climate policy, coordination around DAC is unlikely. Conversely, if the demand is largely satisfied by other CDR methods, its effect on DAC policy remains inconclusive. Given this disagreement, the influence of G3 on H3 is therefore assessed as neutral (zero).

Table 5 of the SI presents the CIB impact matrix, where colors indicate both the direction of influence (either promoting or hindering) and the strength of relationships between variables. Essentially, this figure illustrates how the descriptors in different rows influence the target variables in the corresponding columns.

Table 2. Cross impact matrix of the DAC system in Canada

4- Logical and Mathematical Foundations of Internal Consistency Checks in Cross Impact Balances (CIB) Method

In this section, we describe the internal consistency check carried out by the CIB method, which systematically evaluates all combinations of descriptor variants and identifies those that are perfectly consistent based on predefined logical rules. To illustrate this process, we focus on a subset of our DAC system to keep the example manageable. Specifically, we examine four out of the ten descriptors in the full system: E. Cost of DAC, H. Competitiveness of DAC compared to other CDR methods, I. Public Perception of DAC, and J. Policy Coherence and Cooperation.

Table 3 shows how different variants of these descriptors (rows) influence the variants of the target descriptors (columns). Influence scores range from –3 (strongly hindering) to +3 (strongly promoting).

With four descriptors, each having three variants, there are 81 possible combinations (3^4). Some of these may be internally consistent. For each of the 81 scenarios, a step-by-step consistency check is performed as follows:

1. **Impact Calculation**: For each descriptor, we calculate the total influence that the selected variants of the *other* descriptors exert on each of its possible variants.
2. **Consistency Determination**:
    - If the selected variant receives the highest total impact, the descriptor is considered internally consistent.
    - If another variant receives a higher total impact, the difference becomes the **inconsistency score** for that descriptor.
3. **Scenario Evaluation**:
    - This process is repeated for all descriptors in the scenario.
    - If all descriptors are consistent, the scenario is labeled as internally consistent.
    - If any descriptor is inconsistent, the highest inconsistency score across all descriptors is assigned as the scenario's overall inconsistency score.

Table 3. CIB input matrix for the subset of the DAC problem

	E			H			I			J		
	L	M	H	L	M	H	L	M	H	L	P	H
E. Cost of DAC												
E1- Low				-3	1	2	-1	1	0	0	0	0
E2. Medium				-1	2	-1	0	0	0	0	0	0
E3. High				2	1	-3	3	0	-3	0	0	0
H. Competitiveness of DAC relative to other CDR options												
H1- Low	-2	1	1				2	1	-3	3	-1	-2
H2- Moderate	1	0	-1				-2	1	1	-1	1	0
H3- High	1	1	-2				-3	1	2	-3	1	2
I. Public Perception of DAC												
I1- Low	-2	0	2	3	0	-3				3	-1	-2
I2- Moderate	-1	2	-1	0	0	0				-1	1	0
I3- High	1	1	-2	-2	1	1				-3	1	2
J. Policy Coherence and Cooperation												
J1- Low	-2	0	2	1	0	-1	2	-1	-1			
J2- Partial	0	0	0	-2	1	1	1	0	-1			
J3- High	2	0	-2	-3	1	2	-1	-1	2			

4-1- A consistent scenario example

The scenario being evaluated is characterized by the following active variants:

1. Medium cost of DAC (E2),
2. Moderate competitiveness of DAC compared to other CDR methods (H2),
3. Moderate public perception of DAC (I2)
4. Partial policy coherence (J2).

The rows corresponding to the active variants are highlighted in grey in Table 4.

Evaluating the Consistency of the Selected Variant for Descriptor E (Cost of DAC)

Let's evaluate whether selecting medium cost of DAC (variant E2) is consistent with the rest of the system. To do this, we refer to the column for descriptor E in the matrix and examine how the currently active variants (shown by grey color in Table 3) of the other descriptors influence each possible variant of DAC cost—low (E1), medium (E2), and high (E3).

- Moderate competitiveness of DAC (H2)

  → Impact on E1: +1, E2: 0, E3: –1

- Moderate public perception (I2)

→ Impact on E1: –1, E2: +2, E3: –1

- Partial policy coherence (J2)

  → Impact on all cost variants: 0

Now, summing the influences from all active variants on each cost level:

- Low cost (E1): +1 + (–1) + 0 = 0
- Medium cost (E2): 0 + 2 + 0 = +2
- High cost (E3): –1 + (–1) + 0 = –2

This resulting vector is known as the balance row (shown as the last row in Table 4). Since the medium cost variant (E2) has the highest total influence and is also the selected variant in this scenario, descriptor E is considered internally consistent.

The same consistency check is applied to the other descriptors:

- For H. Competitiveness of DAC, the selected variant is H2 (Moderate), which also has the highest total influence (+3).
- For I. Public Perception of DAC, the selected variant I2 (Moderate) corresponds to the highest score (3), shared with another variant, which is still acceptable in CIB logic.
- For J. Policy Coherence and Cooperation, the selected variant J2 (Partial) also has the highest influence score (2), indicating no inconsistency.

In the balance row, the letter "V" indicates the active variant selected in the scenario. If this "V" aligns with the highest value among the variants for each descriptor, it confirms that the scenario is internally consistent.

4-2- An inconsistent scenario example and the inconsistency score (IS) metric

The scenario being evaluated is characterized by the following active variants:

1. High cost of DAC (E3)
2. High competitiveness of DAC compared to other CDR methods (H3)
3. High public perception of DAC (I3)
4. High policy coherence (J3)

The rows corresponding to the active variants in this scenario are highlighted in grey in Table 5.

Evaluating the Consistency of the Selected Variant for Descriptor E (Cost of DAC)

Let's assess whether selecting high cost of DAC (E2) is consistent with the rest of the system. To do this, we refer to the column for descriptor E in the matrix and examine how the currently active variants (highlighted in grey in Table 5) of the other descriptors influence each possible variant of DAC cost—low (E1), medium (E2), and high (E3).

- High competitiveness of DAC (H3)
  → Impact on E1: +1, E2: +1, E3: -2
- High public perception (I3)
  → Impact on E1: +1, E2: +1, E3: –2
- High policy coherence (J3)
  → Impact on E1: +2, E2: 0, E3: –2

Now, summing the influences from all active variants on each DAC cost level:

- Low cost (E1): 1 + 1 + 2 = +4
- Medium cost (E2): 1 + 1 + 0 = +2
- High cost (E3): –2 + (–2) + (-2) = –6

The resulting vector is called the balance row (shown as the last row in Table 3).

As we can see, all other active variants in the system are collectively pushing the system toward E1 – low cost of DAC, which results in a total impact score of +4. However, the selected variant in this scenario is E3 – high cost, which is poorly supported, with an impact sum of –6. The inconsistency score for this descriptor is calculated as the difference between the highest impact sum and that of the selected variant:

Inconsistency score of descriptor E: +4 – (–6) = 10.

For the other descriptors, we can see that descriptor H is also inconsistent. The system is pushing toward H2 – moderate competitiveness, which has the highest impact sum of +3, while the selected variant in the scenario is H3, with a score of 0. The inconsistency score for descriptor H is therefore 3 – 0 = 3. Descriptors I and J are consistent, as the selected variants align with the highest impact sums for those descriptors. However, because the scenario includes at least one inconsistent descriptor, it is classified as internally inconsistent. The overall inconsistency score for the scenario is the maximum of the individual inconsistency scores across all descriptors. In this case:
max(10, 3) = 10.

Table 4. An example of perfectly consistent scenario

	E			H			I			J		
	L	M	H	L	M	H	L	M	H	L	P	H
E. Cost of DAC												
E1- Low				-3	1	2	-1	1	0	0	0	0
E2. Medium				-1	2	-1	0	0	0	0	0	0
E3. High				2	1	-3	3	0	-3	0	0	0
H. Competitiveness of DAC relative to other CDR options												
H1- Low	-2	1	1				2	1	-3	3	-1	-2
H2- Moderate	1	0	-1				-2	1	1	-1	1	0
H3- High	1	1	-2				-3	1	2	-3	1	2
I. Public Perception of DAC												
I1- Low	-2	0	2	3	0	-3				3	-1	-2
I2- Moderate	-1	2	-1	0	0	0				-1	1	0
I3- High	1	1	-2	-2	1	1				-3	1	2
J. Policy Coherence and Cooperation												
J1- Low	-2	0	2	1	0	-1	2	-1	-1			
J2- Partial	0	0	0	-2	1	1	1	0	-1			
J3- High	2	0	-2	-3	1	2	-1	-1	2			
		v			v			v			v	
Balance:	0	2	-2	-3	3	0	-1	1	0	-2	2	0

Table 5. An example of inconsistent score

	E			H			I			J		
	L	M	H	L	M	H	L	M	H	L	P	H
E. Cost of DAC												
E1- Low				-3	1	2	-1	1	0	0	0	0
E2. Medium				-1	2	-1	0	0	0	0	0	0
E3. High				2	1	-3	3	0	-3	0	0	0
H. Competitiveness of DAC relative to other CDR options												
H1- Low	-2	1	1				2	1	-3	3	-1	-2
H2- Moderate	1	0	-1				-2	1	1	-1	1	0
H3- High	1	1	-2				-3	1	2	-3	1	2
I. Public Perception of DAC												
I1- Low	-2	0	2	3	0	-3				3	-1	-2
I2- Moderate	-1	2	-1	0	0	0				-1	1	0
I3- High	1	1	-2	-2	1	1				-3	1	2
J. Policy Coherence and Cooperation												
J1- Low	-2	0	2	1	0	-1	2	-1	-1			
J2- Partial	0	0	0	-2	1	1	1	0	-1			
J3- High	2	0	-2	-3	1	2	-1	-1	2			
			v			v			v			v
Balance:	4	2	-6	-3	3	0	-1	0	1	-6	2	4

5- Marginally consistent

Within a given scenario, the variant selected for each descriptor is referred to as the active variant, while the alternatives not selected are called non-active variants. The consistency calculation relies on the concept of an impact sum, which represents the total influence a descriptor variant receives from other descriptors, as determined by the cross-impact matrix. The consistency value for a descriptor is calculated by subtracting the highest impact sum among all variants from the impact sum of its active variant. The overall consistency score for a scenario is the lowest consistency value across all its descriptors. Scenarios with consistency scores of 0 or greater are classified as consistent. Any scenario with the negative consistency value is considered inconsistent. In this study, as discussed in Section 4.2.5 of the main text, we considered also looked at the scenarios with an inconsistency score of 1. These new groups, which encompass both perfectly consistent and marginally inconsistent scenarios, are labeled EX1, EX2, and so forth, and are presented in Tables 6, 7, and 8 according to their level of DAC competitiveness (low, moderate, and high). If a scenario in these groups also belongs to the perfectly consistent set in Table 2 of the main text, its original scenario number from Table 2 is shown in the row directly below the EX label. For instance, Table 6 lists 17 scenarios (EX1–EX17), of which 7 (S1–S7) are perfectly consistent and the remaining 10 have an inconsistency score of 1.

Table 6. Perfectly consistent and marginally inconsistent scenarios (indicated by "EX" for extended) where DAC competitiveness is low compared to other CDR methods

Descriptor	Scenarios																
	EX1	EX2	EX3	EX4	EX5	EX6	EX7	EX8	EX9	EX10	EX11	EX12	EX13	EX14	EX15	EX16	EX17
	Equivalent scenario in the Table 2 (perfectly consistent scenarios) of the main text; NA: "Not Available"																
	S1	S2	S3	S4	NA	NA	NA	S5	S6	NA	S7	NA	NA	NA	NA	NA	NA
H. Competitiveness of DAC relative to other CDR options	H1																
I. Public Perception of DAC	I1																
J. Policy Coherence and Cooperation	J1															J2	
D. Carbon Pricing	D1		D2		D3		D2			D3							
E. Cost of DAC	E3						E2			E3	E2				E3		
C. Availability of Other DAC Inputs	C1			C2	C1	C2				C1	C2				C1	C2	
B. Usable Pore Space	B1										B2	B1					
G. National CDR Demand	G1		G2							G3						G2	
F. Market Demand for Products Utilizing Captured CO_2	F1						F2	F3		F1	F2		F3			F2	
A. Supply of Low-Carbon Electricity Inputs	A1	A2		A3	A2	A3		A2	A3	A2		A3	A2	A3	A2		A3

Legend

Low | Moderate/Medium/Partial | High

Table 7. Perfectly consistent and marginally inconsistent scenarios (indicated by “EX” for extended) in which DAC shows moderate competitiveness compared to other CDR methods.

Descriptor	Scenarios									
	EX18	EX19	EX20	EX21	EX22	EX23	EX24	EX25	EX26	EX27
	Equivalent scenario in the Table 2 (perfectly consistent scenarios) of the main text; NA: "Not Available"									
	S8	NA	NA	NA	NA	S9	S10	S11	S12	NA
H. Competitiveness of DAC relative to other CDR options	H2									
I. Public Perception of DAC	I2									I3
J. Policy Coherence and Cooperation	J1	J2								J3
D. Carbon Pricing	D1					D2		D3		
E. Cost of DAC	E2									
C. Availability of Other DAC Inputs	C2									
B. Usable Pore Space	B1			B2	B1	B2				
G. National CDR Demand	G1				G2			G3		
F. Market Demand for Products Utilizing Captured CO_2	F1	F2								F3
A. Supply of Low-Carbon Electricity Inputs	A2	A1	A2				A3	A2	A3	A2

Legend

Low | Moderate/Medium/Partial | High

Table 8. Perfectly consistent and marginally inconsistent scenarios (indicated by “EX” for extended) where DAC competitiveness is high compared to other CDR methods

Descriptor	Scenarios											
	EX28	EX29	EX30	EX31	EX32	EX33	EX34	EX35	EX36	EX37	EX38	EX39
	Equivalent scenario in the Table 2 (perfectly consistent scenarios) of the main text; NA: "Not Available"											
	S13	NA	NA	S14	NA	Na	NA	NA	NA	NA	S15	NA
H. Competitiveness of DAC relative to other CDR options	H3											
I. Public Perception of DAC	I2						I3					
J. Policy Coherence and Cooperation	J2									J3		
D. Carbon Pricing	D2	D3		D2	D3		D2					D1
E. Cost of DAC	E1											
C. Availability of Other DAC Inputs	C2											
B. Usable Pore Space	B3						B2	B3				
G. National CDR Demand	G2	G3					G2		G3	G2	G3	
F. Market Demand for Products Utilizing Captured CO_2	F2			F3								
A. Supply of Low-Carbon Electricity Inputs	A3	A2	A3		A2	A3						

Legend

Low | Moderate/Medium/Partial | High

An example of a marginally inconsistent scenario

Table 9 illustrates why Scenario EX39 (as presented in Table 8) is considered a marginally inconsistent scenario, with an inconsistency score of 1. Examining the influence of the active variants from other descriptors on Descriptor D – Carbon Pricing, we observe that the highest total influence supports the "Moderate" carbon pricing variant (D2), with a sum of 3. However, the selected variant in the scenario is D3 – High carbon pricing, which has a slightly lower influence sum of 2. The inconsistency score for this descriptor is therefore 3 – 2 = 1, indicating a small deviation from internal consistency. Based on the criteria outlined in Section 4.2.5 of the main paper, this scenario is classified as marginally inconsistent.

Table 9. Scenario EX39 as a marginally inconsistent scenario

	A			B			C		D			E			F			G			H			I			J		
	L	M	H	L	M	H	L	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	P	H
A. Supply of Low-Carbon Electricity Inputs																													
A1- Low				3	-1	-2	1	-1	0	0	0	-2	-1	3	0	0	0	0	0	0	2	0	-2	0	0	0	0	0	0
A2- Medium				0	1	-1	-1	1	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3- High				0	0	0	-3	3	0	0	0	2	1	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B. Usable Pore Space																													
B1- Low	0	0	0				0	0	2	-1	-1	-2	-1	3	-1	0	1	0	0	0	3	0	-3	0	0	0	0	0	0
B2- Medium	0	0	0				0	0	0	0	0	-2	3	-1	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
B3- High	0	0	0				0	0	-1	0	1	3	0	-3	1	0	-1	0	0	0	-2	1	1	0	0	0	0	0	0
C. Availability of Other DAC Inputs																													
C1- Low	0	0	0	3	-1	-2			0	0	0	-3	0	3	0	0	0	0	0	0	1	0	-1	1	0	-1	0	0	0
C2- High	0	0	0	-1	0	1			0	0	0	3	0	-3	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0
D. Carbon Pricing																													
D1- Low	1	1	-2	0	0	0	0	0				0	0	0	3	-1	-2	2	-1	-1	0	0	0	0	0	0	3	-1	-2
D2- Medium	-1	0	1	-2	1	1	0	0				0	0	0	-1	-1	2	-3	2	1	0	0	0	0	0	0	-1	1	0
D3- High	-1	0	1	-3	1	2	0	0				0	0	0	-2	-1	3	-3	1	2	0	0	0	0	0	0	-3	1	2
E. Cost of DAC																													
E1- Low	0	0	0	-2	1	1	-1	1	0	0	0				-3	1	2	-2	1	1	-3	1	2	-1	1	0	0	0	0
E2. Medium	0	0	0	-1	1	0	0	0	-1	0	1				-1	2	-1	0	0	0	-1	2	-1	0	0	0	0	0	0
E3. High	0	0	0	1	1	-2	0	0	-2	0	2				2	1	-3	0	0	0	2	1	-3	3	0	-3	0	0	0
F. Market Demands for Products Utilizing Captured CO2																													
F1- Low	0	0	0	0	0	0	0	0	0	0	0	0	0	0				1	0	-1	0	0	0	1	1	-2	0	0	0
F2- Medium	0	0	0	0	0	0	-1	1	0	0	0	0	0	0				0	0	0	0	0	0	-1	1	0	0	0	0
F3- High	0	0	0	0	1	-1	-1	1	1	1	-2	1	1	-2				-2	1	1	-2	1	1	-2	1	1	1	0	-1
G. National CDR Demand																													
G1- Low	0	0	0	2	0	-2	0	0	2	-1	-1	0	0	0	0	0	0				0	0	0	0	0	0	2	1	-3
G2- Medium	-1	1	0	1	0	-1	0	0	-1	2	-1	0	0	0	0	0	0				0	0	0	0	0	0	-2	1	1
G3- High	-1	1	0	-1	0	1	0	0	-3	1	2	1	1	-2	0	0	0				0	0	0	0	0	0	0	0	0
H. Competitiveness of DAC relative to other CDR options																													
H1- Low	0	0	0	2	0	-2	1	-1	0	0	0	-2	1	1	0	0	0	0	0	0				2	1	-3	3	-1	-2
H2- Moderate	0	0	0	1	0	-1	0	0	0	0	0	1	0	-1	0	0	0	-1	1	0				-2	1	1	-1	1	0
H3- High	-1	0	1	-1	0	1	0	0	0	0	0	1	1	-2	0	0	0	-1	0	1				-3	1	2	-3	1	2
I. Public Perception of DAC																													
I1- Low	0	0	0	3	0	-3	0	0	0	0	0	-2	0	2	0	0	0	1	0	-1	3	0	-3				3	-1	-2
I2- Moderate	0	0	0	0	0	0	0	0	0	0	0	-1	2	-1	0	0	0	0	0	0	0	0	0				-1	1	0
I3- High	-1	0	1	-2	0	2	0	0	0	0	0	1	1	-2	0	0	0	-1	0	1	-2	1	1				-3	1	2
J. Policy Coherence and Cooperation																													
J1- Low	0	0	0	3	-1	-2	1	-1	0	0	0	-2	0	2	2	-1	-1	0	0	0	1	0	-1	2	-1	-1			
J2- Partial	0	0	0	1	0	-1	-1	1	0	0	0	0	0	0	-1	2	-1	0	0	0	-2	1	1	1	0	-1			
J3- High	-2	1	1	-2	0	2	-1	1	0	0	0	2	0	-2	-1	-1	2	0	0	0	-3	1	2	-1	-1	2			
			v			v		v			v	v					v			v			v			v			v
Balance:	-6	2	4	-12	3	9	-6	6	-3	2	1	14	5	-19	-5	-1	6	-9	3	6	-13	5	8	-7	2	5	-8	3	5

6- Ensemble Analysis

In the baseline input matrix, we incorporated insights from one expert who suggested that DAC could drive the expansion of clean energy resources—an effect shaped by factors such as competitiveness (H), public perception (I), and policy coherence (J). However, another expert did not perceive a direct influence from these factors on the availability of low-carbon electricity. To capture this alternative perspective, we included scenarios where these positive feedbacks are absent. This divergence underscores the importance of exploring a range of assumptions to gain a more comprehensive understanding of potential future outcomes. The baseline CIB input matrix and the alternative setting are presented in Table 10 as A_v1 and A_v2, respectively.

Regarding the influences on the availability of pore space (Descriptor B), the baseline CIB input matrix incorporates judgments from an expert who argued that the carbon storage process requires energy, and therefore, limited availability of clean energy (Descriptor A) could constrain the expansion of pore space. They also identified a link between the availability of other DAC inputs (Descriptor C) and pore space, noting that shortages in materials and other inputs necessary for DAC could limit the development of storage infrastructure. However, given that pore space is also critical for other CDR methods and, more importantly, for carbon capture and storage (CCS) from point sources, we considered an alternative perspective in which the influences from Descriptors A and C on Descriptor B are removed. The baseline and alternative input matrices are presented in Table 11 as B_v1 and B_v2, respectively.

The influence of policy coherence (J) on carbon pricing (D) is set to zero in the baseline CIB input matrix due to conflicting expert judgments. Expert 1 suggested that a highly integrated policy framework around DAC might employ high carbon prices to promote the technology, but did not see a reciprocal influence of carbon pricing on policy coherence. In contrast, Expert 2 argued that low policy coherence could necessitate the use of higher carbon prices to achieve emissions reductions or negative emissions. To account for these differing mental models, three alternative influence settings were developed: D_v1 (baseline), DJ_v2 (Expert 1), and D_v3 (Expert 2), as summarized in Table 12.

The factorial combinations of these alternative judgments produced 12 distinct CIB input matrices, which served as the foundation for our ensemble analysis. Among the resulting scenarios, 8 emerged as perfectly consistent across all matrices; these are presented in Table 13 and labeled R1 to R8, where

R denotes “robust.” Table 14 lists all scenarios that appeared at least once in the consistent scenario portfolio, labeled U1 to U24, where U denotes “unique.”

Table 10. Alternative judgements for descriptor A

A_v1		A. Supply of Low-Carbon Electricity Inputs		
		Low	Medium	High
Competitiveness of DAC relative to other CDR options	Low	0	0	0
	Medium	0	0	0
	High	-1	0	1
I. Public Perception of DAC	Low	3	0	-1
	Medium	2	0	-1
	High	0	2	3
J. Policy Coherence and Cooperation:	Low	2	0	0
	Medium	2	3	-1
	High	-1	0	3
A_v2		A. Supply of Low-Carbon Electricity Inputs		
		Low	Medium	High
Competitiveness of DAC relative to other CDR options	Low	0	0	0
	Medium	0	0	0
	High	0	0	0
I. Public Perception of DAC	Low	0	0	0
	Medium	0	0	0
	High	0	0	0
J. Policy Coherence and Cooperation:	Low	0	0	0
	Medium	0	0	0
	High	0	0	0

Table 11. Alternative judgements for descriptor B

B_v1		B. Usable Pore Space:		
		Low	Medium	High
A. Supply of Low-Carbon Electricity Input:	Low	3	-1	-2
	Medium	0	1	-1
	High	0	0	0
C. Availability of Other DAC Inputs:	Low	3	-1	-2
	High	-1	0	1
B_v2		B. Usable Pore Space:		
		Low	Medium	High
A. Supply of Low-Carbon Electricity Input:	Low	0	0	0
	Medium	0	0	0
	High	0	0	0
C. Availability of Other DAC Inputs:	Low	0	0	0
	High	0	0	0

Table 12. Alternative judgements for descriptor D and J

		D. Carbon Pricing		
		Low	Medium	High
Policy Coherence (**D_v1**)	Low	0	0	0
	Medium	0	0	0
	High	0	0	0
Policy Coherence **(DJ_v2)**	Low	0	0	0
	Medium	-1	1	0
	High	-3	0	3
Carbon Pricing **(DJ_v2)**		**J. Policy Coherence**		
	Low	0	0	0
	Medium	0	0	0
	High	0	0	0

Policy Coherence **(D_v3)**		**D. Carbon Pricing**		
	Low	-3	1	2
	Medium	0	0	0
	High	0	0	0

Table 13. Robust (R) scenarios in different consistent scenarios sets

Descriptor	**Scenarios**							
	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
H. Competitiveness of DAC relative to other CDR options	H1				H2			
I. Public Perception of DAC	I1				I2			
J. Policy Coherence and Cooperation	J1				J2			
D. Carbon Pricing	D2						D3	
E. Cost of DAC	E3		E2					
C. Availability of Other DAC Inputs	C1	C2						
B. Usable Pore Space	B1				B2			
G. National CDR Demand	G2						G3	
F. Market Demand for Products Utilizing Captured CO_2	F1		F3		F2			
A. Supply of Low-Carbon Electricity Inputs	A2	A3	A2	A3	A2	A3	A2	A3

Legend

Low

Moderate/Medium/Partial

High

Table 14. All unique (U) scenarios identified as consistent across different CIB input matrices

Descriptor	Scenarios																							
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21	U22	U23	U24
H. Competitiveness of DAC relative to other CDR options	H1											H2							H3					
I. Public Perception of DAC	I1												I2								I3			
J. Policy Coherence and Cooperation	J1												J2								J3			
D. Carbon Pricing	D1		D2		D3		D2		D3			D1			D2		D3		D2				D3	
E. Cost of DAC	E3						E2												E1					
C. Availability of Other DAC Inputs	C1			C2	C1	C2																		
B. Usable Pore Space	B1								B2	B1				B2					B3					
G. National CDR Demand	G1		G2						G3			G1			G2		G3		G2	G3				
F. Market Demand for Products Utilizing Captured CO_2	F1						F3		F2	F3		F1	F2							F3				
A. Supply of Low-Carbon Electricity Inputs	A1	A2		A3	A2	A3	A2	A3	A2		A3	A2				A3	A2	A3		A2	A3	A2	A3	

Legend

Low | Moderate/Medium/Partial | High

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