Common LCA/TEA Methodology and Case Studies for Direct Air Capture (DAC)

March 2026

Disclaimer

This document is a government-sponsored technical study report, conducted as part of Japan's contributions to the Mission Innovation (MI) Carbon Dioxide Removal (CDR) Mission.

The drafting of this technical study report was primarily undertaken by the implementing entity commissioned by the Ministry of Economy, Trade and Industry, Japan (METI), and the technical descriptions concerning the methodology and LCA/TEA calculations were prepared with deep involvement by Dr. Shinichirou Morimoto, the National Institute of Advanced Industrial Science and Technology (AIST) and carried out within the MI CDR Mission LCA/TEA technical track, which is jointly led by AIST and Natural Resources Canada (NRCan).

This document does not necessarily reflect the views of MI CDR Mission or its member countries. MI CDR Mission makes no representation or warranty, express or implied, regarding the contents of this document (including its completeness or accuracy), and shall not be responsible for any use of, or reliance on, this document.

This document also does not reflect the views of METI or the organizations and companies mentioned herein.

Acknowledgements

Many individuals were involved in drafting and reviewing sections of this technical study report, including:

Andrew Lenton (CSIRO, Australia), Paul Feron (CSIRO, Australia), Warren Flentje (CSIRO, Australia), Jalil Shadbahr (NRC, Canada), Sean Mccoy (University of Calgary, Canada), Amit Kumar (University of Alberta, Canada), Muntazir Jaffer (DESNZ, United Kingdom), Hatem A. Alhazmi (KACST, Saudi Arabia), Abdullah M Alkhedhair(KACST, Saudi Arabia), and Juho Lipponen (Carbon Dioxide Removal Mission).

Their comments and recommendations were of great value in developing this technical study report.

MI CDR Mission welcomes comments on this report.
Comments can be sent to: mi.cdr@outlook.com

Acronyms and Abbreviations

AIST: National Institute of Advanced Industrial Science and Technology
BiCRS: Biomass Carbon Removal and Storage
CAPEX: Capital Expenditure
CCS: Carbon Capture and Storage
CCUS: Carbon Capture, Utilization, and Storage
CDR: Carbon Dioxide Removal
CFP: Carbon Footprint of Products
DAC: Direct Air Capture
CRF: Capital Recovery Factor
DACCS(DACS) : Direct Air Capture with Carbon Storage
DACS: Direct Air Capture with Storage
DOE: U.S. Department of Energy
EPCC: Engineering, Procurement, and Construction Cost
ERM: Environmental Resources Management
ERW: Enhanced Rock Weathering
GWP: Global Warming Potential
IC: Indirect Cost
IEA: International Energy Agency
IEAGHG: IEA Greenhouse Gas Programme
IMO: International Maritime Organization
IPCC: Intergovernmental Panel on Climate Change

LC: Land Cost
LCA: Life Cycle Analysis/Life Cycle Assessment
LCI: Life Cycle Inventory
LCOC: Levelized Cost of CO_2
LF: Location Factor
METI: Ministry of Economy, Trade and Industry
MI: Mission Innovation
MRV: Monitoring, Reporting, and Verification
NETL: National Energy Technology Laboratory
NPV: Net Present Value
OC: Owner Cost
OCr: Owner Cost Rate
OPEX: Operating Expenditure
RC: Recapitalization Cost
TASC: Total As-spent Capital
TASCr: Total As-spent Capital Rate
TCI: Total Capital Investment
TDIC: Total Direct/Indirect Costs
TEA: Techno-Economic Analysis
TIC: Construction/Installation Cost
TOC: Total Overnight Capital

IRR: Internal Rate of Return

ISO: International Organization for Standardization

IRS: Internal Revenue Service

TPEC: Total Purchased Equipment Cost

VCS: Verified Carbon Standard

Common LCA/TEA Methodology and Case Studies for Direct Air Capture (DAC)

Contents

1. Introduction 7
2. Examination of Prior Research Examples in LCA/TEA for DAC 8
  2.1. U.S. DOE -Best Practices for LCA of DACS[4] 8
    2.1.2. Methodological Approach in Calculation 9
    2.1.3. Sensitivity and Uncertainty Analysis 10
    2.1.4. Multi-Impact and Trade-Off Assessment 10
    2.1.5. Permanence and Monitoring 11
    2.1.6. Policy and Regulatory Integration 11
  2.2. IEAGHG – Global Assessment of DAC Costs[8] 12
    2.2.1. Background and Methodology 12
    2.2.2. Methodological Approach in Calculation (TEA Framework) 12
    2.2.3. Data Sources and Benchmarking Scope 12
    2.2.4. Technology Pathways, Process Assumptions, and Cost Basis 12
    2.2.5. Regionalization, Energy Supply, Transport and Storage, and Key Sensitivities 13
    2.2.6. From Capture Cost to Net Removal and Application 14
  2.3. METI DAC Working Group - Methodology for Direct Air Capture (DAC) of CO_2 from Ambient Air 15
    2.3.1. Background and Methodology 15
    2.3.2. Scope of covered activities and methodology boundary 15
    2.3.3. Key definitions and condition for DAC 15
    2.3.4. Calculation of CO_2 removal 16
    2.3.5. Monitoring requirements 18
3. Development of a Common LCA/TEA Methodology based on Past Studies 19
  3.1 Background and Objectives for Developing the Common LCA/TEA Methodology 19
    3.1.1. Background 19
    3.1.2. Objective 19
  3.2 Details of the Common LCA Methodology 20
    3.2.1. Scope of Common LCA Methodology 20
    3.2.2. Process of Creating Common LCA Methodology 20
    3.2.3. DAC definition and system boundary 22
    3.2.4. Data Collection 26
    3.2.5. GHG accounting method (LCA methodology) 28
  3.3 Details of the Common TEA Methodology 31
    3.3.1. Scope of Common TEA Methodology 31

3.3.2. Data Collection 32
3.3.3 TEA Methodology 33
4. Establishing a Database for Assessing the Potential of CO_2 Removal and Economic Viability for DAC at Country and Regional Levels 37
4.1. Background and Objectives 37
4.2. Data Collection and Process Simulation 37
4.2.1. Data collection and case study design 38
4.2.2. Process Simulation 42
4.2.3. LCA/TEA Methodology for Case Study 45
5. Assessing the Potential of CO_2 Removal and Economic Viability for DAC at Country and Regional Levels 48
5.1. Indicators and Evaluation Framework Linking LCA/TEA 48
5.2. Life-Cycle CO_2 Perspective on Effective Removal 49
5.3. Levelized Cost of CO_2 and Key Cost Drivers 50
5.4. Implications for National and Regional Deployment Strategies 51
6. Conclusion · Action Plan 52
Appendix 1: Literature review with the past survey 54
1. Introduction 54
2. List of DAC-related articles reviewed 54
3. Functional Unit and Emission Scope Harmonization (Cross-Study Comparison between DOE’s best practice of LCA of DACS) 57
3.1. Functional Unit Denominator Differences (per t-CO_2 captured vs per t-CO_2 removed vs product-based FU, etc.) 57
3.2. Functional Unit Numerator / Accounted Flows (gross vs net; what is subtracted/credited) 59
3.3. Emission Scope Mapping (direct / indirect / embodied; inclusion of transport & storage; end-use pathways) 61
3.4. Implications for Comparability and Interpretation 62
3.5. Points of Discussion 64
Appendix 2: Result of the past survey 67

1. Introduction

The purpose of this technical study report is to present the common Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) methodology for Direct Air Capture (DAC) and introduce case studies where the LCA/TEA methodology is utilized to analyze DAC projects in Japan, Australia, Canada, and the United States. According to the State of Carbon Dioxide Removal 2nd edition[1] published in 2024, CDR deployment needs to reach 7-9 Gt CO_2 per year in 2050 to be consistent with the Paris Agreement, while approximately 2 $GtCO_2$ per year of CDR is in place.

However, CDR projects often face a common challenge of being unable to accurately quantify CO_2 reductions, resulting in uncertainty about their effectiveness. In addition, DAC projects frequently entail high costs and lack business viability. For example, although there have been previous studies that evaluated the CO_2 removal potential and costs of various CDR approaches (Fuss et al., 2018[2]; Hepburn et al., 2019[3]), none of them have sufficiently addressed the uncertainties arising from the diverse conditions inherent to CDR projects. In addition, guidelines for LCA and TEA of CDR technologies, including DAC, have been developed and discussed within various national and international frameworks, such as those by the U.S. Department of Energy (DOE)[4], Environmental Resources Management (ERM)[5], Puro Earth[6], and Verified Carbon Standard (VCS)[7]. However, there remains a need to comprehensively synthesize these existing guidelines and establish a methodology that can be commonly applied across countries and institutions, in order to facilitate the development of multinational CDR projects and promote investment in CDR.

To address this challenge, as part of a research project underway at AIST, case studies analyzing DAC projects across multiple countries were conducted on the basis of a standardized methodology. This technical study report explains how the methodology

---

[1] Smith, S.M., Geden, O., Nemet, G.F., et al. (2024) *The State of Carbon Dioxide Removal: Second Edition*. London: University of Oxford, Smith School of Enterprise and the Environment. Available at: https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/665ed1e2b9d34b2bf8e17c63/1717490167773/The-State-of-Carbon-Dioxide-Removal-2Edition.pdf

[2] Sabine Fuss, Negative emissions—Part 2: Costs, potentials and side Effects, *Environ. Res. Lett.* 13 (2018)

[3] Hepburn, C., Adlen, E., Beddington, J. *et al.* (2019) The technological and economic prospects for CO_2 utilization and removal. *Nature* 575, 87–97

[4] U.S. Department of Energy (2022). Best Practices for Life Cycle Assessment of Direct Air Capture with Storage (DACS). Available at: https://www.energy.gov/hgeo/best-practices-life-cycle-assessment-direct-air-capture-storage-dacs

[5] Environmental Resources Management (2022). Greenhouse Gas Removal (GGR) Monitoring, Reporting and Verification (MRV): Review of Methodologies and Practices. Final report. Available at: https://www.sustainability.com/contentassets/8ac6f4f2d36c4305bbd130c21763a239/ggr-mrv-review-by-erm---final-report-for-publication-v2.pdf

[6] Puro.earth (2025). Direct Air Capture and Ocean Storage Methodology for CO2 Removal: Public Consultation Document. Available at: https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Public%20Consultations/DACOS%20Public%20Consulation.pdf

[7] Verra (2023). Verified Carbon Standard (VCS) Program Standard: Overview. Available at: https://verra.org/program-methodology/vcs-program-standard/overview/

was developed and how it could be applied to assess the project's viability and effectiveness. This study is intended to advance international projects based on DAC and, in the longer term, to the mobilization of a certain level of investment, which could contribute to achieving the goals of the Paris Agreement.

2. Examination of Prior Research Examples in LCA/TEA for DAC

DAC is increasingly recognized as a vital technology in the global effort to achieve net-zero carbon emissions, as outlined in international climate mitigation roadmaps. Given the urgency to deploy CDR at gigatonne scale, robust analytical frameworks are needed to ensure credibility, comparability, and policy relevance. LCA and TEA are fundamental tools used to assess the environmental performance and economic viability of DAC projects.

LCA quantifies the potential environmental impacts of DAC throughout its life cycle, while TEA evaluates the associated costs and techno-economic parameters. Both methodologies complement each other: LCA focuses on environmental outcomes, such as net CO_2 removal and broader ecological impacts, and TEA provides insights into economic feasibility and scalability. However, harmonizing these approaches is essential for effective decision-making, as different studies often use inconsistent boundaries, metrics, and assumptions.

This technical study report highlights DOE[4] and the IEAGHG calculation guidelines[8] and reports as case examples that could serve as advanced and internationally applicable methodologies based on LCA/TEA. It also introduces the methodologies developed by the Mission Innovation CDR Mission (MI CDR Mission) LCA/TEA technical track and METI, which prepared this technical study report.

2.1. U.S. DOE -Best Practices for LCA of DACS[4]

2.1.1. Background and Scope

DOE has been a global leader in developing and disseminating best practices for LCA of Direct Air Capture with Storage (DACS). Recognizing the unique characteristics and challenges of DAC—including low atmospheric CO_2 concentrations, high energy requirements, and the need for permanent geological storage—the DOE published a comprehensive guideline for LCA of DACS in 2022.

---

[8] IEA Greenhouse Gas R&D Programme (2021). Global Assessment of Direct Air Capture Costs. Technical Report 2021-05. Available at: https://publications.ieaghg.org/technicalreports/2021-05%20Global%20Assessment%20of%20Direct%20Air%20Capture%20Costs.pdf

2.1.2. Methodological Approach in Calculation

DOE's methodological framework for LCA is adapted from ISO 14040[9]/14044[10] standards and tailored to the specific context of DAC. The main steps are:

- **Goal and Scope Definition:** Clearly state the purpose of the LCA (e.g., technology comparison, regulatory compliance) and set the functional unit as "one metric ton of CO_2 captured and permanently stored."
- **System Boundary Setting**: Use a rigorous "cradle-to-grave" boundary that includes raw material acquisition, plant construction, DAC operation, CO_2 compression, transport, waste management, and geological storage. (Figure 1)
- **Life Cycle Inventory (LCI):** Collect high-quality primary and secondary data on material and energy flows, chemical usage, emissions, and co-products. Ensure regional specificity and transparency.
- **Impact Assessment:** Quantify environmental impacts using standardized characterization factors, primarily Global Warming Potential (GWP), but also water use, land use, and resource depletion as appropriate.
- **Sensitivity and Scenario Analysis:** Conduct scenario modelling and sensitivity tests to evaluate how changes in energy mix, capture efficiency, and regional conditions affect results.
- **Reporting and Transparency:** Document all assumptions, data sources, and calculation procedures; ensure reproducibility and facilitate third-party review.
- **MRV Integration:** Include Monitoring, Reporting, and Verification for CO_2 permanence and leakage risk.

This methodology ensures that the environmental performance of DAC projects is assessed consistently, transparently, and in accordance with international standards.

---

[9] International Organization for Standardization (2006). ISO 14040: Environmental management — Life cycle assessment — Principles and framework. ISO, Geneva. Available at: https://www.iso.org/standard/37456.html

[10] International Organization for Standardization (2006). ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. ISO, Geneva. Available at: https://www.iso.org/standard/38498.html

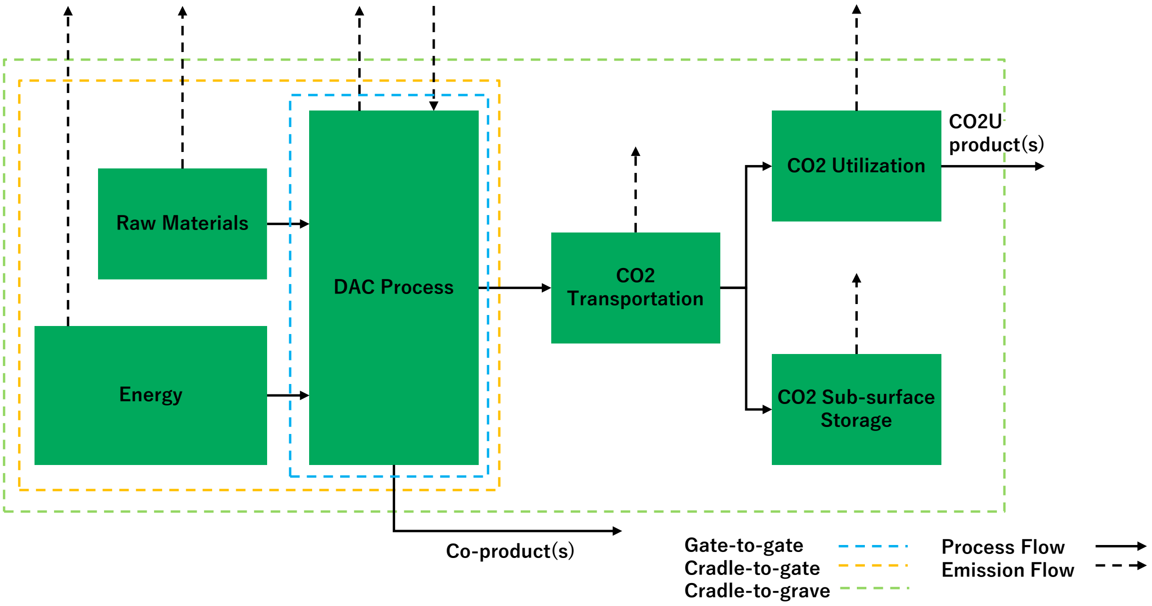


Figure 1 System boundary examples for direct air capture (DAC) [4]

2.1.3. Sensitivity and Uncertainty Analysis

All assumptions regarding energy sources (renewable/fossil), regional factors, and process design must be clearly documented.

- **Energy Mix Impact**: Studies show that the net GHG removal efficiency of DAC can vary widely with the electricity grid's carbon intensity. For instance, solid sorbent DAC plants powered by coal-based grids may achieve only 50–60% net removal, while those powered by renewables can exceed 90%.
- **Scenario Modelling**: DOE best practices recommend scenario analysis to assess the effect of future energy mixes, technology improvements, and regional differences.
- **Regionalization**: Local water availability, land use, and proximity to CO_2 storage sites are critical and should be included in LCA boundaries.

2.1.4. Multi-Impact and Trade-Off Assessment

DOE's guidelines stress the need to assess multiple environmental impact categories beyond GHGs, such as:

- **Water Use:** DAC processes can be water-intensive, especially liquid solvent systems.
- **Land Use:** Large-scale deployment may have significant land footprint, particularly for facilities powered by renewables.

- **Resource Depletion:** Manufacturing and deployment of DAC units require metals and chemicals; their sourcing and disposal must be included.

2.1.5. Permanence and Monitoring

Permanent storage is a cornerstone of DAC's climate benefit. DOE LCA best practices require:

- **Inclusion of Monitoring, Reporting, and Verification (MRV)**: LCA must account for the risk of CO_2 leakage, monitoring protocols, and long-term storage reliability.
- **Geological Storage**: Analysis of the suitability and security of geological formations.

2.1.6. Policy and Regulatory Integration

DOE's LCA guidance is now referenced in U.S. regulatory frameworks, such as the IRS 45Q tax credit for utilization. Projects must demonstrate robust LCA and MRV to qualify for incentives.

2.2. IEAGHG – Global Assessment of DAC Costs[8]

2.2.1. Background and Methodology

The IEAGHG Technical Report "Global Assessment of Direct Air Capture Costs" (2021-05) is a landmark international study that systematically reviews the techno-economic performance of DAC technologies across regions, feedstocks, and energy systems. The report synthesizes data from leading DAC companies, published literature, and process modeling, providing a harmonized basis for cost and energy benchmarking.

2.2.2. Methodological Approach in Calculation (TEA Framework)

IEAGHG's assessment is grounded in a TEA framework tailored to DAC. The framework organizes costs and performance drivers into:

- **Plant CAPEX**: construction, equipment, engineering, and commissioning
- **OPEX**: energy, labour, maintenance, and consumables
- **Energy requirements**: detailed breakdowns of electricity and heat demand
- **CO_2 transport and storage**: costs for compression, pipeline transport, and geological storage

2.2.3. Data Sources and Benchmarking Scope

The report synthesizes data from leading DAC companies, published literature, and process modeling to establish a harmonized basis for benchmarking both cost and energy intensity. This integrated evidence base supports consistent cross-study and cross-region comparisons of DAC performance.

2.2.4. Technology Pathways, Process Assumptions, and Cost Basis

The IEAGHG assessment differentiates DAC technologies primarily by their capture and regeneration mechanisms because these determine the balance of heat versus electricity demand and, consequently, both operating and capital costs. Liquid solvent systems—typified by alkaline absorption followed by precipitation and high-temperature calcination—exhibit substantial high-temperature heat requirements alongside moderate electrical loads for blowers, pumps, and solids handling. Solid sorbent systems—using amine-functionalized media or analogous porous materials—rely on low- to moderate-temperature heat for desorption and comparatively higher electricity use for fans and vacuum equipment. Across both pathways, the report imposes common boundary conditions to ensure comparability, including target CO_2 purity and delivery pressure, compression specifications to reach transport or storage conditions, and consistent design throughput, turndown capability, and availability assumptions.

Cost reporting is normalized to facilitate cross-study and cross-region comparisons. Two metrics are emphasized: capture cost, expressed per tonne of CO_2 produced at the plant boundary, and removal cost, expressed per tonne of net CO2 removed after deducting lifecycle emissions. Capital expenditures are presented as overnight costs with transparent inclusion of engineering, procurement and construction, owner's costs, and contingencies, while operating costs are separated into fixed (labor, maintenance) and variable (electricity, heat, chemicals, sorbent make-up) components. Annualization follows a declared capital recovery framework with explicit discount rates, lifetimes, and tax treatments. This normalization prevents differences in accounting conventions from obscuring underlying technology and site effects.

2.2.5. Regionalization, Energy Supply, Transport and Storage, and Key Sensitivities

IEAGHG explicitly regionalizes its cases to reflect the heterogeneity of energy markets, grid carbon intensity, storage access, and policy environments. Electricity supply options range from grid-sourced power to contracted renewables and hybrids, recognizing that hourly variability and curtailment influence realized capacity factors, specific energy use, and energy price outcomes. Heat sourcing is pathway-specific: solvent routes require high-temperature heat for calcination and consider natural gas (with or without oxy-combustion), electrified kilns, biomass, or solar thermal integration; solid sorbent routes generally require lower-temperature heat, allowing more straightforward electrification or opportunistic use of waste heat.

The analysis also standardizes assumptions for multi-stage intercooled compression from process conditions to pipeline or storage pressures. Beyond the plant gate, the assessment models compression and dehydration, pipeline transport with cost functions dependent on capacity, length, diameter, and right-of-way, and storage elements including site characterization, wells and completions, injection operations, monitoring, and long-term stewardship. Where multiple projects can access shared hub infrastructure, significant economies of scale are recognized in transport and storage costs.

Sensitivity analysis highlights a common set of decisive drivers. Electricity and heat prices, together with their carbon intensities, dominate operating costs and materially affect net removal when lifecycle deductions are applied. Capacity factor and operating strategy determine capital productivity and can alter specific energy use if cycling or part-load operation is frequent. Sorbent or solvent degradation rates and make-up requirements influence consumables costs and waste management, particularly for solid sorbents exposed to ambient humidity and oxygen. Scale and learning effects shift equipment costs and operating practices over time, while financing terms and contingency policies change the annualized capital burden. Regional climate conditions that affect air contactor performance—such as temperature and humidity—are acknowledged because they alter adsorption capacity, regeneration loads, and throughput, with downstream implications for both costs and emissions.

2.2.6. From Capture Cost to Net Removal and Application

In this report, a central methodological step is the conversion from capture-based economics to removal-based economics. Net CO_2 removal is computed by deducting lifecycle emissions—principally from electricity and heat use, but also from materials, construction, transport, storage operations, and expected leakage—from the captured quantity. The levelized cost of net removal is then calculated as the ratio of annualized total costs to annual net removal. Because higher energy carbon intensity simultaneously raises operating costs and reduces net removal, securing low-carbon electricity and appropriately matched low- or high-temperature heat is pivotal to lowering removal costs and achieving robust climate performance. Consistent with IEAGHG's reporting conventions, both capture and removal metrics should be disclosed to maintain transparency and to align with crediting approaches focused on net benefit.

2.3. METI DAC Working Group - Methodology for Direct Air Capture (DAC) of CO_2 from Ambient Air[11]

2.3.1. Background and Methodology

To achieve carbon neutrality by 2050, negative-emission technologies such as Direct Air Capture with Carbon Storage (DACCS) are needed to offset unavoidable residual emissions. At the point of carbon-neutral achievement, it is expected that CO_2 removal by DACCS will need to be valued in a way that ensures DACCS activity itself is net-negative when evaluated across the full life cycle. However, at the current early stage of market formation, it is also necessary to promote early demonstration and social implementation of DAC technology while seeking accuracy in quantification and reflecting the current technology readiness and regulation-development status. This methodology is therefore prepared by the METI DAC working group from the perspective of accelerating early social implementation and industrialization, while recognizing that revisions may be required as technologies and related systems evolve.

2.3.2. Scope of covered activities and methodology boundary

This methodology covers activities that remove CO_2 from the atmosphere by directly capturing atmospheric CO_2 and then storing/fixing it (e.g., via storage). For the boundary of this DAC methodology within the working group, the scope is defined from the moment CO_2 is captured from the air up to the DAC equipment and conditioning/delivery facilities. Separately, because quantifying DACCS removal requires inclusion through transport and storage, the quantification boundary for removal includes transport and storage facilities; for those facilities, the methodology follows separately defined CCS (and related) methodologies.

2.3.3. Key definitions and condition for DAC

This methodology may be applied only when all conditions are satisfied.

Condition 1 (Atmospheric origin): Captured CO_2 must be atmospheric in origin. “Atmosphere” means air that is not directly influenced by a fixed emission source (e.g., power-plant stack, factory exhaust), while local anthropogenic/natural influences may still cause CO_2 concentration variability; indoor air is included. The project proponent must reasonably explain atmospheric capture by combining one or more approaches, such as: confirming sufficient distance from fixed emission sources using maps; monitoring the CO_2 concentration of the source gas and confirming it does not

---

[11] Ministry of Economy, Trade and Industry, Japan (2024). Direct Air Capture Working Group: Methodology for Direct Air Capture (DAC) of CO_2 from Ambient Air [in Japanese]. Available at: https://www.meti.go.jp/shingikai/energy_environment/negative_emission/dac_wg/pdf/005_s01_00.pdf

significantly deviate from the atmospheric CO_2 concentration; or confirming non-deviation based on sorbent/equipment capability, operating records, and capture performance. If CO_2 from non-atmospheric sources is also captured, the methodology may still be applied if the amount captured from the atmosphere can be identified.

Condition 2 (Eligible capture technologies and regeneration): The capture method must use a technology capable of capturing CO_2 from air and extracting it at a high concentration (e.g., chemical absorption, chemical adsorption, membrane separation, electrochemical, physical adsorption, physical absorption). Approaches that use materials that are not regenerated (e.g., capture materials permanently fixed as part of a structure) are out of scope.

Condition 3 (New fossil-fuel heat equipment): If new fossil-fuel equipment is installed to secure the required heat, a CO_2 capture unit must also be installed; installing a new fossil-fuel combustion device without capture is not allowed. The capture unit must achieve at least the average capture rate of multiple representative technologies (in principle, three or more) available at the project start.

Condition 4 (Compliance and sustainability): The project must comply with relevant laws/regulations across capture, transport, and storage/fixation steps, and must ensure sustainability through environmental and social considerations (examples of relevant laws are listed in the source).

2.3.4. Calculation of CO_2 removal

CO_2 removal is calculated as:

$$\boldsymbol{ER} = \boldsymbol{RM_{PJ}} - \boldsymbol{EM_{PJ}} \tag{1}$$

where $\boldsymbol{ER}$ is removal (tCO_2/year), $\boldsymbol{RM_{PJ}}$ is the amount stored/fixed by the project (tCO_2/year), and $\boldsymbol{EM_{PJ}}$ is project emissions (tCO_2/year). Emission activities to consider include emissions from CO_2 capture energy use, CO_2 transport energy use, CO_2 storage/fixation energy use.

Calculation of stored/fixed CO_2 attributable to the project ($\boldsymbol{RM_{PJ}}$)
Stored/fixed CO_2 attributable to the project is calculated as:

$$\boldsymbol{RM_{PJ}} = \boldsymbol{ST_{DACCS}} \times, \boldsymbol{R_{PJ1}} \times, \boldsymbol{R_{PJ2}} \tag{2}$$

$\boldsymbol{ST_{DACCS}}$ is the CO_2 stored/fixed amount (tCO_2/year). $\boldsymbol{R_{PJ1}}$ is the share of the total stored/fixed CO_2 that comes from CO_2 captured by the project; $\boldsymbol{R_{PJ2}}$ is the share of the project-captured CO_2 that is atmospheric in origin. Monitoring of injection quantity must be conducted at the storage/fixation site; quantities monitored elsewhere (e.g., capture amount) must not be used as ST_{DACCS}. If all monitored CO_2 is from the project, R_{PJ1} may be set to 1; if all captured CO_2 is atmospheric, R_{PJ2} may be set to 1.

It is important to clarify the treatment of potential leakage from geological storage within this framework. In the METI methodology, ST_{DACCS} represents the monitored amount of CO_2 injected at the storage site. The methodology explicitly states that detailed monitoring regulations for the storage site, which would include the accounting for any long-term leakage, are to follow a separately defined CCS methodology. Therefore, the METI DAC methodology itself does not contain the specific formula for deducting storage-site leakage; it defers this critical aspect to the linked CCS framework.

Furthermore, the factor R_{PJ1} is an allocation factor used to differentiate the project's CO_2 from other sources in a co-storage scenario, and is not a leakage factor. $R_{PJ1} = 1$ signifies that 100% of the injected CO_2 originates from the project being assessed.

Calculation of project emissions (EM_{PJ})
Project emissions may be represented as:

$$EM_{PJ} = EM_{PJ,capture} + EM_{PJ,transport} + EM_{PJ,storage} \tag{3}$$

For transport and storage emissions, this methodology requires alignment with separately defined CCS (etc.) methodologies.
For emissions from CO_2 capture (energy use), the methodology provides:

$$EM_{PJ,capture} = F_{PJ,cap} \times HV_{PJ,cap} \times CEF_{PJ,cap} + EL_{PJ,cap} \times CEF_{electricity,t} + EM_{PJ,heat_{supply}} \tag{4}$$

$$EM_{PJ,heat_{supply}} = Q_{PJ,heat} \times \beta_{PJ} \times CEF_{PJ,heat\ sypply} \tag{5}$$

$$Q_{PJ,heat} = FL_{PJ,heat} \times \Delta T_{PJ,heat} \times C_{PJ,heat} \times \rho_{PJ,heat} \times 10^{-3} \tag{6 − 1}$$

$$Q_{PJ,heat} = FL_{PJ,heat} \times \Delta H_{PJ,heat} \times 10^{-6} \tag{6 − 2}$$

$EM_{PJ,capture}$: CO_2 emissions associated with energy use during CO_2 capture (tCO_2/year).
$F_{PJ,cap}$: Fuel consumption during CO_2 capture (e.g., kL/year, t/year, m^3/year).
$HV_{PJ,cap}$: Heating value of the fuel used during CO_2 capture (e.g., GJ/t, GJ/kL, GJ/Nm^3).
$CEF_{PJ,cap}$: CO_2 emission factor per unit of fuel heating value for the fuel used during CO_2 capture (tCO_2/GJ).
$EL_{PJ,cap}$: Electricity consumption during CO_2 capture (MWh/year).
$CEF_{electricity,t}$: CO_2 emission factor for electricity at time (t) (tCO_2/MWh).
$EM_{PJ,heat_{supply}}$: CO_2 emissions associated with the use of externally supplied heat (e.g., steam) for CO_2 capture (tCO_2/year).
$Q_{PJ,heat}$: Amount of heat supplied at the inlet of the heat demand point (GJ/year).
β_{PJ} : Primary energy conversion factor for heat supply (MJ/MJ).
$CEF_{PJ,heat_{supply}}$: CO_2 emission factor per unit of fuel heating value for the fuel used in the

heat-supply equipment (tCO_2/GJ).
$FL_{PJ,heat}$: Flow rate of hot water or heat transfer oil delivered to the heat user (m^3/year).
$\Delta T_{PJ,heat}$: Temperature difference of the hot water or heat transfer oil before and after heat use (K).
$C_{PJ,heat}$: Specific heat capacity of the hot water or heat transfer oil (MJ/(t·K)).
$\rho_{PJ,heat}$: Density of the hot water or heat transfer oil (t/m^3).
$\Delta H_{PJ,heat}$: Enthalpy difference of steam before and after use (kJ/kg).

The capture-stage scope may include the use of auxiliary facilities installed at the project site (e.g., air separation, water treatment, steam systems, renewable energy equipment), fans for airflow generation, regeneration of capture media, storage facilities for CO_2 before transport, and pre-treatment to make captured CO_2 suitable for transport/storage (processing after transport begins is counted in transport). Additionally, when using renewables that satisfy the stated conditions, eligible unused waste heat, electricity with non-fossil certificates/green certificates, and unused waste heat, the corresponding emission activities may be treated as zero.

The methodology also provides rules for simplifying monitoring based on “impact” (ratio of emissions to removal): if impact is ≥5%, emissions must be monitored and calculated; if 1% to <5%, monitoring may be omitted but emissions are calculated by multiplying removal by the impact; if <1%, emissions calculation may be omitted.

2.3.5. Monitoring requirements

The methodology specifies monitoring items and example methods/frequencies for

(i) activity data (e.g., stored/fixed CO_2 amount, fuel/electricity use for capture, supplied heat quantity, etc.) and

(ii) coefficients (e.g., RpJ1, RpJ2, fuel heating value and CO_2 factors, electricity CO_2 factor, etc.).

3. Development of a Common LCA/TEA Methodology based on Past Studies

3.1 Background and Objectives for Developing the Common LCA/TEA Methodology

3.1.1. Background

Carbon dioxide mitigation at global scale requires cross-border collaboration and a shared analytic foundation. Numerous CDR projects are emerging worldwide, and LCA/TEA is essential for large-scale implementation.

Therefore, various methodologies and guidelines have been developed and examined for evaluating CDR from the perspectives of LCA and TEA. While these approaches share certain common elements, they also differ in terms of scope, system boundaries, data collection methods, and functional units. In recent years, international projects based on CDR technologies, such as DAC, have been increasingly established, and this trend is expected to continue. Under such circumstances, if different guidelines are applied to evaluate different projects, uncertainty increases, and it becomes difficult to explain differences in evaluation results across projects. This, in turn, complicates corporate decision-making and ultimately hinders the development of voluntary CDR credit markets as well as opportunities for large-scale investment.

Considering these challenges, this technical study report addresses the need for greater consistency by proposing a common LCA/TEA methodology. The objective is not to create a single, exclusive standard, but rather to provide a practical and consistent framework to support comparable evaluation and decision-making, particularly for cross-boundary CDR projects. This proposed methodology is the result of analyzing, synthesizing, and consolidating key elements from existing guidelines, and is intended to facilitate collaboration among countries, complementing other ongoing standardization efforts at national and regional levels.

3.1.2. Objective

In light of the above circumstances, this technical study report presents the common LCA/TEA methodology developed under MI CDR Mission LCA/TEA Technical Track. The purpose of establishing a harmonized LCA/TEA methodology is to enable effective decision-making when developing international projects across different countries and institutions, and ultimately to contribute to the achievement of the Paris Agreement goals by facilitating market development and promoting investment.

While CDR encompasses a range of approaches beyond DAC, including enhanced rock weathering (ERW) and biomass carbon removal and storage (BiCRS), these technologies differ significantly in their technical characteristics, making it challenging to apply a single unified LCA/TEA methodology across all CDR options. Therefore, within MI CDR Mission, efforts began with the development of a common methodology specifically for DAC as a first step.

3.2 Details of the Common LCA Methodology

3.2.1. Scope of Common LCA Methodology

A common LCA methodology and guidelines have been outlined to facilitate international collaboration and large-scale investment in DAC. This harmonized methodology defines key elements such as the framework, scope, system boundaries, data collection, functional units, Greenhouse Gas (GHG) accounting methods, and evaluation criteria.

The ISO standards for LCA—particularly ISO 14040[9], ISO 14044[10], and ISO 14067[12]—specify that environmental aspects and potential impacts should be assessed across the entire life cycle of a product, from raw material acquisition through production, use, and end-of-life. ISO 14040 describes the principles and framework of LCA, ISO 14044 sets out requirements and guidelines, and ISO 14067 addresses the carbon footprint of products (CFP). The common LCA methodology presented in this technical study report is based on these standards, and its specific scope draws on a range of previously examined methodologies, as discussed later in this technical study report.

In particular, the common LCA methodology described herein focuses primarily on GHG accounting based on the CFP approach. This involves quantifying all relevant GHG emissions (e.g., CO_2, CH_4, N_2O) across the life cycle and expressing them in CO_2 equivalents (CO_2e) to calculate a carbon footprint. To maintain this focus, this methodology does not include impact assessment, sensitivity analysis, or MRV methodologies, as addressed in guidelines such as those developed by DOE[4].

3.2.2. Process of Creating Common LCA Methodology

Efforts to develop a common LCA/TEA methodology began in 2022. In constructing the common LCA methodology, existing DAC-related accounting guidelines were reviewed as reference cases, including those developed by DOE[4], IEAGHG[8], VCS[7], International Sustainability and Carbon Certification (ISCC)[13], ERM[5], Puro.earth[6], and Climeworks[14].

---

[12] International Organization for Standardization (2018). ISO 14067: Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. ISO, Geneva.Available at: https://www.iso.org/standard/71206.html

[13] International Sustainability and Carbon Certification (2025). ISCC EU 205: Greenhouse Gas Emissions, Version 4.2. ISCC, Cologne. Available at: https://www.iscc-system.org/wp-content/uploads/2025/04/ISCC_EU_205_Greenhouse_Gas_Emissions_v4.2.pdf

[14] Climeworks. (2022). Direct Air Capture Methodology. Climeworks AG, Available at: https://climeworks.com/uploads/documents/direct-air-capture-methodology_climeworks_2022-1692890675.pdf

It is important to acknowledge that the field of CDR accounting is evolving rapidly. Several significant new methodologies and standards have emerged, particularly focused on the certification and market integrity of carbon removals. These include the EU Carbon Removal Certification Framework (CRCF)[15], the UK's British Standards Institute (BSI) standard for DACCS[16], and frameworks from the Integrity Council for the Voluntary Carbon Market (ICVCM) and Article 6.4 of the Paris Agreement[17].

This technical report's proposed methodology aligns with the core GHG accounting principles of those frameworks. Its primary focus, however, is distinct. It is specifically designed to integrate LCA with TEA to provide a consistent basis for informing investment decisions and supporting the commercialization of cross-boundary DAC projects. This focus on combining environmental and economic assessment for project development differs from the primary purpose of the newer certification-oriented standards.

In addition, more than 20 existing research studies were surveyed with respect to their system boundaries, functional units, and evaluation methods, and commonly applied scopes were identified. (Details of the past survey described here are presented in Appendix 2)

Based on these findings, meetings were held within the LCA/TEA Technical Track with CDR researchers representing the United States, Canada, Australia, the United Kingdom, Saudi Arabia, and other countries. Through these discussions, key methodological elements, as well as the scope, functional unit, and evaluation approaches to be included in the methodology, were harmonized.

Note: The scope of this common LCA methodology is focused on GHG accounting based on the CFP approach and does not include impact assessment. Users are therefore encouraged to conduct additional multi-impact assessments separately where relevant. In particular, in water-scarce regions, assessing water-related impact categories (e.g., water use / water resource depletion) is recommended to reflect regional conditions and to support robust interpretation alongside net CO2 removal results.

---

[15] European Commission (2026) *EU sets world's first voluntary standard for permanent carbon removals*. Available at: https://climate.ec.europa.eu/news-other-reads/news/eu-sets-worlds-first-voluntary-standard-permanent-carbon-removals-2026-02-03_en (Accessed: 15 March 2026).

[16] BSI Group (2025) PAS 2090:2025, Pharmaceutical products. Product category rules for life cycle assessments. Specification. Available at: https://knowledge.bsigroup.com/products/pharmaceutical-products-product-category-rules-for-life-cycle-assessments-specification (Accessed: 15 March 2026)

[17] Martirosian, N, Thoppil, MA, Mouchos, E, House, J, Smart, J, Johnstone, I, Štrubelj, L & Butnar (2025) *Alignment of international standards for carbon dioxide removal (CDR) using Carbon Capture and Storage (CCS): Comparative analysis of the EU Carbon Removal and Carbon Farming (CRCF) Regulation against the Integrity Council for the Voluntary Carbon Market (ICVCM) and Article 6.4 of the Paris Agreement*. CO2RE. https://doi.org/10.71706/92435e1c-c500-43ce-be95-1007565ebc7a

In addition to the sensitivity analysis performed in this report's case studies to identify key influential parameters, a complete LCA study should also incorporate Uncertainty Analysis. Uncertainty analysis is distinct from sensitivity analysis; it aims to quantify the confidence range of the final results (e.g., net carbon removal) by propagating the known uncertainty of input data through the model. Methodologies such as Monte Carlo simulations[18] can be used to determine a probabilistic distribution for the final GHG balance, providing a range of likely outcomes rather than a single point estimate. Although a detailed methodology for uncertainty analysis is not established in this version of the report, practitioners are encouraged to incorporate it. Developing a harmonized approach to uncertainty analysis for DAC projects is a key area for future work.

A detailed methodology for uncertainty analysis is not established in this version of the report. Nevertheless, practitioners are encouraged to incorporate it, as developing a harmonized approach to uncertainty analysis for DAC projects is a key area for future work.

3.2.3. DAC definition and system boundary

The definition of DAC adopted in this technical study report is as follows.

VCS[7] specifies that CO_2 must be captured from "ambient air" as the source of capture and defines DAC as "a process to capture and concentrate atmospheric CO_2 using various separation methods."

Puro.earth[6] does not provide a specific definition regarding the source of CO_2 capture, while Climeworks[14] identifies the atmosphere as an eligible CO_2 capture source but does not explicitly define the influence of emissions from point sources.

For these reasons, MI CDR Mission defines DAC as a "technology or system to capture CO_2 from the atmosphere," without explicitly specifying or restricting the influence of point sources.

The system boundaries considered in this technical study report are illustrated in Figure 2 and Figure 3. Figure 2 defines the system boundary up to the capture of CO_2 from the atmosphere, while Figure 3 extends the boundary to include CO_2 treatment.
The flow covers upstream emissions (fossil, non-fossil, land-use), utilities (electricity/heat), chemicals and make-up, water supply and wastewater treatment,

---

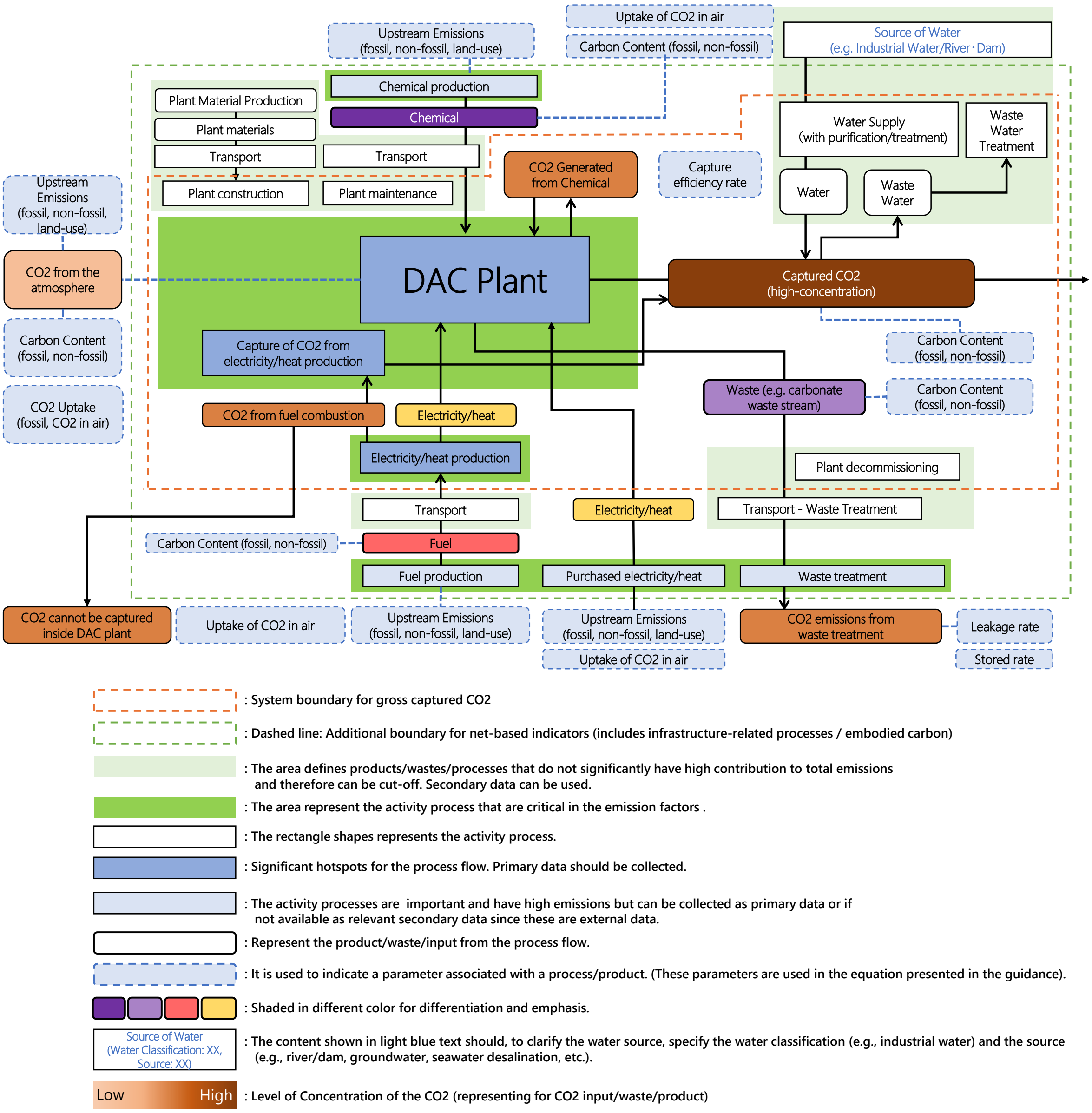
[18] Di Lullo, G., Gemechu, E., Oni, A.O. *et al.* (2020) Extending sensitivity analysis using regression to effectively disseminate life cycle assessment results. *Int J Life Cycle Assess* **25**, 222–239. https://doi.org/10.1007/s11367-019-01674-y

CO2 uptake from air (low concentration) through to captured CO_2 (high concentration), and waste streams. Identified high-contribution items/processes—such as electricity/heat supply, capture steps, and specific chemicals—should be prioritized for primary data collection; items with low contribution may rely on disclosed secondary data.

Electricity and heat supply are included within the system boundary as utilities, together with their upstream emissions (e.g., generation mix and fuel type). This applies to both purchased utilities and on-site generation supplying the DAC plant.

In the scope of after CO_2 treatment (Figure 3), transport, storage, and utilization of CO2 in products are included. CO2 utilization is identified as an important process and should preferably use primary data. Leakage rates at each stage, as well as fossil and non-fossil carbon content, are included within the assessment boundary.

Water supply and wastewater treatment are included in the system boundary. As the upstream process for Water Supply can vary depending on the assumed water source and treatment, the system boundary and related inventory items may be updated accordingly.



⬚ : System boundary for gross captured CO2

⬚ : Dashed line: Additional boundary for net-based indicators (includes infrastructure-related processes / embodied carbon)

▨ : The area defines products/wastes/processes that do not significantly have high contribution to total emissions and therefore can be cut-off. Secondary data can be used.

🟩 : The area represent the activity process that are critical in the emission factors .

▭ : The rectangle shapes represents the activity process.

🟦 : Significant hotspots for the process flow. Primary data should be collected.

▭ : The activity processes are important and have high emissions but can be collected as primary data or if not available as relevant secondary data since these are external data.

▢ : Represent the product/waste/input from the process flow.

⬚ : It is used to indicate a parameter associated with a process/product. (These parameters are used in the equation presented in the guidance).

🟪🟪🟥🟨 : Shaded in different color for differentiation and emphasis.

Source of Water (Water Classification: XX, Source: XX) : The content shown in light blue text should, to clarify the water source, specify the water classification (e.g., industrial water) and the source (e.g., river/dam, groundwater, seawater desalination, etc.).

Low High : Level of Concentration of the CO2 (representing for CO2 input/waste/product)

Figure 2: System Boundary for Common LCA Methodology (1)

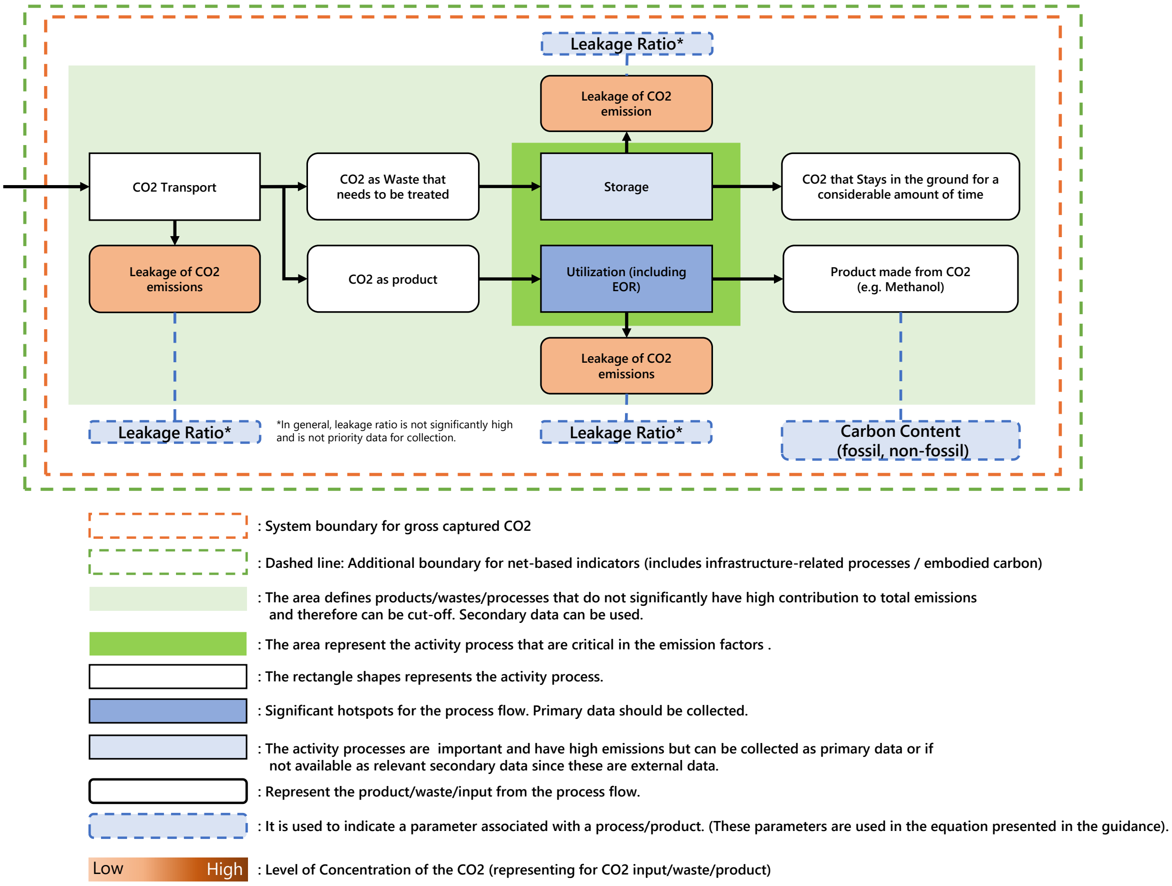


Figure 3: System Boundary for Common LCA Methodology (2)

In this LCA methodology, embodied carbon (infrastructure-related processes such as plant construction, maintenance, and decommissioning) is included within the assessment scope for net-based indicators, i.e., indicators that deduct life-cycle emissions from the captured/removed CO_2. For transparency, projects shall also report the gross captured CO_2 separately as a plant performance indicator, noting that embodied carbon may be excluded from such gross reporting. In addition, within the system boundary shown in Figure 2, embodied carbon associated with fuel extraction facilities and chemical production plants is excluded. Although inclusion would, in principle, align with the definition, the assessment scope will be expanded to incorporate embodied carbon from fuel extraction and chemical production infrastructure once data collection becomes sufficiently feasible.

Where adequate primary or secondary data are not available, temporary exclusion of embodied-carbon items is permitted only with transparent disclosure of (i) the rationale, (ii) the excluded items, and (iii) their expected contribution; such items shall be incorporated as data availability improves.

3.2.4. Data Collection

(1) CO_2 capture (from outside the plant)

The origin of the CO_2 captured from the atmosphere, distinguishing between fossils and atmospheric CO_2, should be collected. The capture efficiency (if any) should also be collected. The final output concentration of captured CO_2 (high concentration) must be determined. The concentration of CO_2 (low concentration) from the atmosphere should also be determined.

(2) Purchased energy inputs

Any CO_2 uptake in air, as well as the fossil/non-fossil/land-use components of upstream emissions related to purchased electricity/heat, should be collected as primary data. The production process and mix of electricity/heat production should also be disclosed. (If primary data on the purchased electricity/heat are unavailable, the production method and fuel type of the electricity/heat should be collected.) If secondary data has been used, the details of that process must also be disclosed.

When renewable electricity/heat is supplied, the corresponding emission factors should be based on LCA databases or disclosed life-cycle inventories and should not be assumed to be zero.

(3) Fuel inputs

Any CO_2 uptake in air, as well as the fossil/non-fossil/land-use components of upstream emissions related to fuel production, should be collected.

The fossil/non-fossil carbon content of the fuels should be collected.

If the fuels are combusted to produce electricity/heat for the DAC plant, the CO2 emissions and their fate (emitted to air OR captured and incorporated into the output product) should be collected.

If an internal CO_2 capture facility is applied to capture the CO2 from fuel combustion, the capture efficiency rate of that CO2 capture facility should be collected.

(4) Chemical inputs

Any uptake of CO_2 in the air, as well as the fossil/non-fossil/land-use components of upstream emissions related to chemical production, should be collected as primary data.

The fossil/non-fossil carbon content of the chemicals should be collected.

If the chemicals are used in a reaction that results in net CO_2 emissions, CO_2 generated from the chemicals (captured and included in the output product, included in the waste, or leaked and emitted into the air) should be collected. The type of Solvent/Sorbent chemicals used in the DAC plant should be determined. The amount of makeup chemicals used in the processes would vary depending on the type of solvent/sorbent makeup added, especially in the precipitation reaction. This includes solvent/sorbent materials; the type and amount of solvent/sorbent chemicals should be collected as primary data.

(5) Consistent approach for waste & water/wastewater

(A) Make identification of waste streams mandatory

The project shall identify waste generated from DAC plant (e.g., solvent/sorbent-derived wastes, carbonate waste streams), indicate whether they contain fossil or non-fossil carbon, specify the treatment routes (e.g., landfill), and collect primary data or appropriate secondary data. The project shall collect CO2 emissions associated with waste treatment (e.g., modeling CO2 leakage when carbonates are landfilled) and establish rules for how to handle the time dimension.

(B) Handling when “waste is valorized outside the boundary”

When waste is utilized as a separate product outside the system boundary (i.e., treated as a by-product rather than as waste), explicitly state that route as the assumed scenario (counterfactual) and apply by-product treatment (e.g., allocation) as appropriate. And avoid inconsistent treatment such as placing only waste treatment outside the boundary while keeping water supply/wastewater inside; follow the consistency rules in (C).

(C) Consistency with water supply and wastewater treatment

In this LCA methodology, water supply and wastewater treatment are included in the system boundary. If the end use/treatment of wastes is detailed as out-of-boundary processes, apply the same logic to explicitly state assumptions for the water supply processes (source and treatment assumptions) and the wastewater treatment processes, and update the inventory items

(6) Infrastructure-related processes (Embodied carbon)

When assessing embodied carbon, a distinction should be made between the DAC facility itself and the upstream infrastructure for its inputs.

1.The DAC facility itself:

The GHG emissions from the construction, maintenance, and decommissioning of the new DAC plant should be included in the assessment. This is particularly important because the operational lifetime of a new facility may be uncertain, which can significantly influence the annualized impact of its embodied carbon.

Where data gaps prevent robust quantification and contributions are expected to be immaterial, a cut-off may be applied. In such cases, practitioners must provide:
(i) justification for the exclusion,
(ii) a qualitative screening or proxy estimate where feasible, and
(iii) an explicit note on whether significant land-use change is involved.

2.Upstream infrastructure for inputs:
For inputs such as chemicals, materials, or energy, it is assumed they are produced in existing, long-life industrial facilities. Therefore, practitioners are not required to collect primary data for the construction of this upstream infrastructure. Instead, the impact of capital goods for these inputs should be accounted for through the use of established LCI databases, which typically include such background processes.

(7) Downstream processes
Treatment of downstream processes (CO2 conditioning, transport, storage, and utilization) depends on the reporting purpose. Downstream processes may be excluded for plant-gate indicators; however, for net removal, downstream emissions and leakage shall be included and deducted. This applies even when downstream operations are conducted by a third party, in which case MRV-based data and assumptions shall be transparently documented.

3.2.5. GHG accounting method (LCA methodology)

In DAC, the amount of CO_2 removal is limited to CO_2 that is captured directly from the atmosphere, and it must be clearly distinguished from “reductions” in CO_2 emissions based on fossil fuels. The DOE’s guidelines[4] also state that “The differentiation of removed and avoided emissions is of critical importance for assessing the efficacy of potential CDR technologies”.

In GHG accounting, emissions from biogenic sources require careful treatment. Following the principles of the IPCC Guidelines[19], any biogenic GHG emissions within the project boundary must be reported separately as an information item. However, for the purpose of calculating the net carbon removal delivered by the DAC project, these biogenic CO_2 emissions are treated as carbon neutral to avoid double-counting the carbon already present in the biogenic cycle. This approach distinguishes them from fossil-fuel-derived emissions. Non-CO_2 GHGs from biogenic sources are not considered neutral and must be included in the project emissions.

Waste and unused energy are treated in a similar manner, depending on their origin (biogenic or fossil).

In cases where co-products are generated during CO_2 capture, allocation should be applied in accordance with the DOE guidelines[4], which state that systems should “partition (allocate) the inputs and outputs of the system in a way that reflects the

---

[19] IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

underlying physical relationships between them." Typical bases for establishing such physical relationships include mass and energy value. When a physical relationship cannot be established, an alternative allocation basis—such as economic value—should be used.

This principle is also reflected in other guidelines for carbon capture and utilization or storage (CCUS) and CDR. For example, International Maritime Organization (IMO) guideline[20] state that "when more than one product results from a conversion process, emissions related to the fuel production should be allocated between the main product and co-products. Within such conversion processes, emissions are allocated using their energy content, the so-called 'energy allocation' approach. Where co-product allocation cannot be performed based on their energy content (e.g. oxygen resulting from water electrolysis for H_2 production), other methods such as mass allocation or market revenue allocation (also known as 'economic allocation') could be considered on a case-by-case basis." Therefore, this technical study report adopts the same allocation approach.

The method for estimating the amount of CO_2 removal is based on methodologies published by various organizations, with primary reference to the approaches issued by DOE[4] and METI[11] as described above.

When the amount represents carbon removal from the air (i.e., the origin is exclusively atmospheric CO_2), the net carbon removal from air, $\boldsymbol{CR_{air}}$(tCO_2e/year), is calculated using (7).
In (7), the mass of removed and stored CO_2 ($\boldsymbol{RM_{air}}$) is covered to CO2 equivalents by applying its GWP of 1, to ensure consistent units across all terms.

$$\boldsymbol{CR_{air} = RM_{air} - EM_{PJ}} \tag{7}$$

$\boldsymbol{EM_{PJ}}$: Project emissions (tCO_2e/year). Emission activities to consider include emissions from CO_2 capture energy/chemical use, CO_2 transport energy/chemical use, CO_2 storage/fixation energy/chemical use and overall waste treatment energy/chemical use.

$\boldsymbol{RM_{air}}$: Stored/fixed CO_2 attributable to the project and it's origin is from air (tCO_2/year).
Note: This term represents the mass of pure CO_2 removed from the atmosphere and stored. For the purpose of GHG accounting in CO_2 equivalents, its GWP is treated as 1.

When the amount represents CO_2 removal from the project (i.e., the origin includes not

---

[20] International Maritime Organization (2024) *MEPC.391(81): 2023 Guidelines on the lifecycle GHG intensity of marine fuels (LCA guidelines)*. London: IMO. Available at: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.391(81).pdf

only atmospheric CO_2 but also CO_2 generated within the system), the net carbon reduction from the project, CR_{PJ} (tCO_2/year), is calculated using (8).

$$CR_{PJ} = RM_{PJ} - EM_{PJ} \tag{8}$$

RM_{air} is derived from RM_{PJ} using the atmospheric fraction f_{air} , as shown in (9).

$$RM_{air} = RM_{PJ} \times f_{air} \tag{9}$$

F_{air}: Fraction of the project's stored/fixed CO_2 (RM_{PJ}) that originates from ambient air (dimensionless). Thus, (9) where $0 \leq F_{air} \leq 1$.

The project emissions (EM_{PJ}) are calculated using (10).

$$EM_{PJ} = EM_{PJ,capture} + EM_{PJ,transport} + EM_{PJ,storage} + EM_{PJ,waste} \tag{10}$$

For transport and storage emissions, this methodology requires alignment with separately defined CCS (etc.) methodologies.
For emissions from CO_2 capture, transport, storage, and waste, the methodology provides:

$$\begin{aligned} EM_{PJ,capture} = {} & F_{PJ,cap} \times HV_{PJ,cap} \times CEF_{PJ,cap} \\ & + EL_{PJ,cap} \times CEF_{electricity,t} + EM_{PJ,heat_{supply}} \\ & + EL_{PJ,chemical} \times CEF_{PJ,chemical} \end{aligned} \tag{11}$$

$$\begin{aligned} EM_{PJ,transport} = {} & F_{PJ,transport} \times HV_{PJ,transport} \times CEF_{PJ,transport} + EL_{PJ,transport} \\ & \times CEF_{electricity,t} \end{aligned} \tag{12}$$

$EM_{PJ,transport}$: GHG emissions from CO_2 transport under the project (tCO_2e/year)
$F_{PJ,transport}$: Amount of fuel consumed for CO_2 transport under the project (t/year)
$HV_{PJ,transport}$: Net calorific value of the fuel used for CO_2 transport (GJ/t)
$CEF_{PJ,transport}$: GHG emission factor of the fuel used for CO_2 transport (tCO_2e/GJ)
$EL_{PJ,transport}$: Electricity consumption for CO_2 transport under the project (MWh/year)
$CEF_{electricity,t}$: GHG emission factor of electricity in year t (tCO_2e/MWh)

$$EM_{PJ,storage} = F_{PJ,storage} \times HV_{PJ,storage} \times CEF_{PJ,storage} + EL_{PJ,storage} \times CEF_{electricity,t} \tag{13}$$

$EM_{PJ,storage}$: GHG emissions from CO_2 storage under the project (tCO_2e/year)
$F_{PJ,storage}$: Amount of fuel consumed for CO_2 storage under the project (t/year)
$HV_{PJ,storage}$: Net calorific value of the fuel used for CO_2 storage (GJ/t)
$CEF_{PJ,storage}$: GHG emission factor of the fuel used for CO_2 storage (tCO_2e/GJ)
$EL_{PJ,storage}$: Electricity consumption for CO_2 storage under the project (MWh/year)

$CEF_{electricity,t}$: GHG emission factor of electricity in year *t* (tCO$_2$e/MWh)

$$EM_{PJ,waste} = Q_{PJ,waste} \times CEF_{PJ,waste} + EL_{PJ,waste} \times CEF_{electricity,t} \tag{14}$$

$EM_{PJ,waste}$: GHG emissions from waste treatment under the project (tCO$_2$e/year)
$Q_{PJ,waste}$: Quantity of waste treated under the project (t/year)
$CEF_{PJ,waste}$: GHG emission factor for waste treatment (tCO$_2$e/t)
$EL_{PJ,waste}$: Electricity consumption for waste treatment under the project (MWh/year)
$CEF_{electricity,t}$: GHG emission factor of electricity in year *t* (tCO$_2$e/MWh)

$$EP_{PJ,heat\_supply} = Q_{PJ,heat} \times \beta_{PJ} \times CEF_{PJ,heat\_supply} \tag{15}$$

$EP_{PJ,heat\_supply}$: GHG emissions from heat supply under the project (tCO$_2$e/year)
$Q_{PJ,heat}$: Quantity of heat supplied under the project (GJ/year)
β_{PJ}: Fossil carbon share of the supplied heat under the project
$CEF_{PJ,heat\_supply}$: GHG emission factor of heat supply (tCO$_2$e/GJ)

The functional unit recommended by DOE is "the mass of CO2 captured from the atmosphere and permanently stored," and in this technical study report, it use the mass-based RM_{air} (7). and CR_{PJ} (8) as primary indicators.

As a supplementary performance indicator, (16) is reported as "net carbon removal effectiveness (ηDAC)", which is dimensionless (kgCO$_2$e/kgCO$_2$) and should not be interpreted as a mass-based functional unit. The interpretation is that ηDAC = -1 is ideal (EM_{PJ}=0), ηDAC = 0 indicates net zero ($EM_{PJ} = RM_{air}$), and ηDAC > 0 indicates that net emissions exceed removals.

$$\eta DAC = \frac{(EM_{PJ} - RM_{air})}{RM_{air}} \tag{16}$$

3.3 Details of the Common TEA Methodology

3.3.1. Scope of Common TEA Methodology

The project aims to standardize TEA methods and parameters to enable global dissemination and comparison of results.

In developing the common TEA methodology, existing methodologies and guidelines were referenced, in the same manner as for the LCA methodology, and these were consolidated to establish a common TEA methodology for MI CDR Mission.
The references consulted include the IEAGHG Technical Reports[8] and the NETL's Direct Air

Capture Case Studies[21], as well as methodologies and tools from the hydrogen sector[22], the NETL cost estimation model[23], and Aspen Icarus[24].

As the process definition and system boundary are identical to those defined in the common LCA methodology, they are not described in this technical study report. Instead, this technical study report focuses solely on data collection requirements and calculation methods.

3.3.2. Data Collection

(1) CAPEX

To estimate CAPEX for DAC systems, data on the Total Purchased Equipment Cost (TPEC) must first be collected. Using this value together with data on the construction/installation cost rate, indirect costs rate, process contingency rate, and project contingency rate, the Fixed Capital Investment (Total Plant Cost) can be calculated (the detailed calculation method is described in the next section).

Furthermore, to derive the Total Overnight Capital from the Fixed Capital Investment, data on the owner's cost rate, location factor, and land cost are required.
In addition, estimation of annualized CAPEX and cash flow requires data on depreciation and the discount rate.

Within MI CDR Mission, these data elements are classified into those that are applied in common across participating countries and those that must be collected on a country-specific basis.

As a result, the Total Purchased Equipment Cost is treated as a common dataset, while all other parameters listed above are collected as country-specific data, in order to reflect differences in national economic conditions.

---

[21] National Energy Technology Laboratory (2022) Direct Air Capture Case Studies: Sorbent System. Pittsburgh, PA: NETL, U.S. Department of Energy. Available at: https://www.netl.doe.gov/projects/files/DirectAirCaptureCaseStudiesSorbentSystem_070822.pdf

[22] IEA Greenhouse Gas R&D Programme (2017) Techno-Economic Evaluation of SMR-Based Standalone (Merchant) Hydrogen Plant with CCS. Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme (IEAGHG). Available at: https://publications.ieaghg.org/technicalreports/2017-02%20Techno%20-%20Economic%20Evaluation%20of%20SMR%20Based%20Standalone%20(Merchant)%20Hydrogen%20Plant%20with%20CCS.pdf

[23] National Energy Technology Laborator (2024) *FECM NETL CO_2 Transport Cost Model: Description and User's Manual.* National Energy Technology Laboratory, U.S. Department of Energy. Available at: https://netl.doe.gov/projects/files/FECMNETLCO2TransportCostModel2024DescriptionandUsersManual_082324.pdf

[24] Aspen Technology, Inc. (2024) Aspen Process Economic Analyzer (Aspen Icarus). Bedford, MA: Aspen Technology, Inc. Available at: https://aspen-icarus.software.informer.com/

(2) OPEX

To estimate OPEX for DAC systems, energy costs and raw material (chemical) costs must be determined.

As data on fuel, electricity, and other heat consumption are already collected as part of the LCA data collection, the additional data required for cost estimation are country-specific unit prices for fuel, electricity, and other heat sources.

In addition, estimation of OPEX requires the collection of data on labor costs, maintenance costs, waste disposal costs, insurance and property taxes, administrative and overhead costs, end-of-life expenses, and fixed and variable operating expenses, within the system boundary defined in Figure 2 and Figure 3 (CO_2 capture, transport, storage, and waste management).

As economic conditions vary by country, these data shall be collected on a country-specific basis.

A full OPEX estimation should include all components listed in the next section. However, in the early stages of a project when detailed data for items like maintenance or administrative costs may not be available, a preliminary estimate of OPEX is permitted. In such cases, the calculation must, at a minimum, include the most significant variable costs: Energy Cost and Raw Material Cost. The exclusion of any other OPEX items must be explicitly justified, and its potential impact on the final levelized cost of CO_2 should be noted.

3.3.3 TEA Methodology

For TEA of DAC systems, the levelized cost of CO_2 is used as the primary evaluation metric in the IEAGHG Technical Reports[8] and the NETL's Direct Air Capture Case Studies[21]. In addition, net present value (NPV) and internal Rate/factor of return (IRR) are defined as supplementary economic indicators.

When CO_2 removed from the atmosphere is stored or permanently fixed, carbon credit transactions may take place, generating potential revenue.

Therefore, within MI CDR Mission, the calculation method for NPV is also described.

The methodology for CAPEX estimation is defined as follows.

$$TIC = TPEC \times TIC_r \qquad (17)$$

TIC: Construction/Installation Cost
$TPEC$: Total Purchased Equipment Cost
TIC_r: Construction/Installation Cost Factor

$$IC = TPEC \times IC_r \tag{18}$$

IC: Indirect cost
IC_r: Indirect cost Factor

$$TDIC = TIC + IC = TPEC \times \left(1 + (TIC_r + IC_r)\right) \tag{19}$$

$TDIC$: Total Direct/Indirect Costs

$$Proc_{Con} = TDIC \times Proc_{Cr} \tag{20}$$

$Proc_{Con}$: Process Contingency
$Proc_{Cr}$: Process Contingency Factor

$$Proj_{Con} = (TDIC + Proc_{Con}) \times Proj_{Cr} \tag{21}$$

$Proj_{Con}$: Project Contingency
$Proj_{Cr}$: Project Contingency Factor

$$FCI = TDIC + Proc_{Con} + Proj_{Con} \tag{22}$$

FCI (TPC): Fixed Capital Investment (Total Plant Cost)

Here, in the NETL cost model, TDIC is defined as Engineering, Procurement, and Construction Cost (EPCC), and the method is also described in which an engineering, procurement, construction, and management factor is applied to the TPEC.

In addition, Total Overnight Capital (TOC) and Total As-spent Capital (TASC) are calculated using the following equations. TASC is treated as CAPEX.

$$\begin{gathered} TOC\ (TCI) = FCI \times (1 + OC_r) + FCI \times LF = FCI + OC + LC \\ TASC = TOC \times TASC_r \end{gathered} \tag{23}$$

TOC: Total Overnight Capital
TCI: Total Capital Investment
OC: Owner Cost
OC_r: Owner Cost factor
LF: Location Factor
LC: Land Cost
$TASC$: Total As-spent Capital
$TASC_r$: Total As-spent Capital factor

OPEX shall be calculated as follows.

$$OPEX = EC + RMC + LAC + MC + WDC + IPT + AOC + ELE + FVOE \tag{24}$$

All cost items are annual costs (currency/year) within the system boundary. In particular, $\boldsymbol{EC}$ (energy cost), $\boldsymbol{RMC}$ (raw material cost), and $\boldsymbol{LAC}$ (labor cost) should be collected and calculated based on annual consumption within the defined system boundary. For all other items, data collection is prescribed (shall) but they are not mandatory.

$\boldsymbol{OPEX}$: Operating Expense
$\boldsymbol{EC}$: Energy Cost
$\boldsymbol{RMC}$: Raw Material Cost
$\boldsymbol{LAC}$: Labor Cost
$\boldsymbol{MC}$: Maintenance Cost
$\boldsymbol{WDC}$: Waste Disposal Cost
$\boldsymbol{IPT}$: Insurance and Property Tax
$\boldsymbol{AOC}$: Admin/Overhead Cost
$\boldsymbol{ELE}$: End of Life Expense
$\boldsymbol{FVOE}$: Fixed & Variable Operating Expense

In this TEA methodology, OPEX includes $\boldsymbol{MC}$. However, expenditures for repurchasing or replacing major equipment at intervals (e.g., every 5 or 10 years) are defined separately as Recapitalization Cost $(\boldsymbol{RC})$ and reflected in the annual cash flows and in $\boldsymbol{TC}$. Specifically, either record the expenditure as a negative in the free cash flow for the renewal year $(\boldsymbol{CF_n})$, or model it as a CAPEX time series allocated by year and add it to $\boldsymbol{TC}$.

Using the CAPEX and OPEX calculated from the above equations, LCOC and the net present value (NPV) can be calculated using the following equations, assuming a project lifetime of "$\boldsymbol{t}$".

$$\boldsymbol{TC = \sum_t \frac{(OPEX + CAPEX)_t}{(1+r)^t}} \qquad (25)$$

$\boldsymbol{TC}$: Total cost
$\boldsymbol{r}$: Discount factor

$$\boldsymbol{TNCR = \sum_t \frac{CR_{air\ t}}{(1+r)^t}} \qquad (26)$$

$\boldsymbol{TNCR}$: Total of Net CO_2 removal
$\boldsymbol{CR_{air}}$: Net carbon removal from air (tCO_2e/year)

$$\boldsymbol{LCOC = \frac{TC}{TNCR}} \qquad (27)$$

$\boldsymbol{LCOC}$: Levelized cost of CO_2

Note on LCOC Calculation Method: This technical study report uses a discounted cash flow (DCF) approach to calculate LCOC, which accounts for the time value of money by discounting all future costs and CO_2 removals to a present value. An alternative, simpler approach is the Annualized Cost Method, which uses a Capital Recovery Factor (CRF) to annualize CAPEX and combines it with annual OPEX. While both methods yield similar results under consistent assumptions, the DCF approach is adopted here as it explicitly models the cash flows over the project's lifetime, providing a comprehensive financial perspective.

$$NPV = \sum_{n=1}^{t} \frac{CF_n}{(1+r)^n} - CF_0 \tag{28}$$

$\boldsymbol{NPV}$: Net Present Value
$\boldsymbol{CF_n}$: Free Cash Flow, Net cash flow in Year n
$\boldsymbol{CF_o}$: Initial investment, total upfront CAPEX at Year 0

4. Establishing a Database for Assessing the Potential of CO_2 Removal and Economic Viability for DAC at Country and Regional Levels

4.1. Background and Objectives

This chapter presents case studies in which LCA and TEA were conducted for DAC across ten regions, based on the LCA/TEA methodology described in Chapter 3.

These case studies were carried out as part of the activities of MI CDR Mission, with the objective of clarifying the regional characteristics of DAC. By identifying such regional characteristics, the studies aim to support the global expansion of DAC investment and promote the development of international projects. However, it should be noted that several evaluation studies on DAC already exist, and therefore this case study does not claim academic novelty. For example, cost evaluations have already been conducted in the IEAGHG Technical Reports[8] and the NETL's Direct Air Capture Case Studies[21], and assessments of the impacts of climatic conditions on DAC costs have also been published at the global level[25][26] as well as in U.S.-focused studies[27].

Nevertheless, it is important to demonstrate a comprehensive process for evaluating the large-scale deployment potential of CDR technologies, taking regional characteristics into account, through an international collaborative framework such as Mission Innovation. The purpose of this report is to contribute to investment facilitation and the creation of international DAC projects by providing a detailed description of MI CDR Mission's activities, including the harmonization of LCA/TEA methodologies, data collection, definition of evaluation frameworks, and evaluation processes for assessing the large-scale implementation potential of CDR technologies.

4.2. Data Collection and Process Simulation

The DAC system discussed in this technical study report is based on Carbon Engineering's KOH-based direct air capture technology[28]. Ten regions with diverse climatic conditions were selected from four countries worldwide, and the amount of CO_2

---

[25] An, K., Farooqui, A. and McCoy, S.T. (2022) 'The impact of climate on solvent-based direct air capture systems', Applied Energy, 325, 119895. doi:10.1016/j.apenergy.2022.119895.

[26] Sendi, M., Bui, M., Mac Dowell, N. and Fennell, P. (2022) 'Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment', One Earth, 5(10), pp. 1153–1164. doi:10.1016/j.oneear.2022.09.003.

[27] Brooks, B.-G., Geissler, C.H., An, K., McCoy, S.T., Middleton, R.S. and Ogland-Hand, J.D. (2024) 'The performance of solvent-based direct air capture across geospatial and temporal climate regimes', Frontiers in Climate, 6, 1394728. doi:10.3389/fclim.2024.1394728.

[28] Keith, D.W., Holmes, G., St. Angelo, D. and Heidel, K. (2018) *A process for capturing CO_2 from the atmosphere*. Joule, 2(8), pp. 1573–1594. Available at: https://www.sciencedirect.com/science/article/pii/S2542435118302253

captured and the levelized cost of CO_2 removal were evaluated using the LCA/TEA methodology described in Chapter 3.

Process simulations were conducted using Aspen Plus[29], based on the climatic conditions of the ten regions (average temperature and average humidity), to estimate energy consumption, utility consumption, and equipment costs. Based on these simulation results, parameters required for TEA, including country-specific energy costs, were collected from MI CDR Mission. The results are presented in this section.

4.2.1. Data collection and case study design

In the data collection process, ten regions with diverse climatic conditions were first selected from four countries worldwide. For each region, meteorological data including average temperature, maximum temperature, minimum temperature, and average humidity were collected. These ten regions (Figure 4) were selected such that the relationships between temperature and humidity were not similar across regions, as summarized in Table 1.

Meteorological data were obtained from publicly available datasets published by the United States[30][31], Canada[32][33], Australia[34], and Japan[35], and the resulting climatic conditions for each region are presented in Table 1.

---

[29] Aspen Technology, Inc. (n.d.) Aspen Plus. Available at: https://www.aspentech.com/products/engineering/aspen-plus

[30] Climate-Data.org (n.d.) Climate: El Paso (Texas, United States). Available at: https://en.climate-data.org/north-america/united-states-of-america/texas/el-paso-943/ (Accessed: 19 August 2025)

[31] Climate-Data.org (n.d.) Climate: Miami (Florida, United States). Available at: https://en.climate-data.org/north-america/united-states-of-america/florida/miami-1641/ (Accessed: 19 August 2025)

[32] Climate-Data.org (n.d.) Climate: Edmonton (Alberta, Canada). Available at: https://en.climate-data.org/north-america/canada/alberta/edmonton-610/ (Accessed: 19 August 2025)

[33] Climate-Data.org (n.d.) Climate: Estevan (Saskatchewan, Canada). Available at: https://en.climate-data.org/north-america/canada/saskatchewan/estevan-956/ (Accessed: 19 August 2025)

[34] Australian Government Bureau of Meteorology (n.d.) Climate statistics for Australian locations: Station 085280. Available at: http://www.bom.gov.au/climate/averages/tables/cw_085280.shtml(Accessed: 19 August 2025)

[35] Japan Meteorological Agency (n.d.) Normal values (monthly) – Surface observation. Available at: https://www.data.jma.go.jp/obd/stats/etrn/view/nml_sfc_ym.php?prec_no=21&block_no=47424 (Accessed: 19 August 2025)

Figure 4 Selected regions in four countries

Table 1: Climate conditions of 10 locations

Country	City	Ave Tempeature (Unit : ℃)	Max Tempeature (Unit : ℃)	Min Tempeature (Unit : ℃)	Ave Humidity (Unit : %)
Japan	Tomakomai	7.9	11.8	4.1	77.0
	Fukuoka	17.3	21.3	14.0	68.0
Australia	Traralgon	10.1	20.2	8.3	68.5
	Moomba	22.6	29.5	15.6	32.5
	Millimerran	18.3	25.6	11.0	54.0
Canada	Edmonton	3.1	8.6	-1.3	69.0
	Estevan	4.4	10.1	-0.2	67.0
	Sarnia	9.4	13.2	6.1	71.1
United States	El Paso	18.3	25.5	11.3	32.3
	Miami	24.9	27.0	18.2	72.5

In this technical study report, process simulations of DAC are conducted based on the selected climatic conditions to estimate energy consumption, utility consumption, and equipment costs. In addition, data for TEA were collected as summarized in Table 2.

The costs of renewable energy were based on reports published by IEA[36] as well as various datasets obtained through MI CDR Mission. Fuel costs were assumed to be

---

[36] IEA (2022), "Levelised Cost of Electricity Calculator", IEA, Paris, https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-electricity-calculator (Retrieved July 8, 2025)

liquefied natural gas (LNG) and were referenced from publicly available data sources[37][38][39]. The costs of KOH and $CaCO_3$ were adopted from the results of a DAC case study conducted in Japan[40], and the same values were applied across all countries.

Labor costs were set based on publicly available data for manufacturing wages in each country[41], with values of **USD 29.51/h** for the United States, **CAD 32.08/h** for Canada, **AUD 1,716/week** for Australia, and **JPY 362,412/month** for Japan. Labor costs were calculated, assuming ten full-time workers employed annually.

Some reference sources and parameter values used in this technical study report, other than those explicitly cited above, are not individually referenced within the technical study report.

The case-study dataset includes average temperature and humidity, equipment purchase values, electricity/fuel/water prices, carbon credits, depreciation rates, and federal/state tax rates for each location. For instance, Tomakomai shows equipment purchase of about $371.6M, electricity $0.06/kWh, fuel gas roughly $584/t, industrial water $0.15/t, carbon credits $200/t, depreciation rate 3%, and a federal/state tax rate of 23%. Comparable entries appear for the other sites, such as lower electricity prices in Canada and the U.S. ($0.04/kWh) and higher carbon credits in Canada ($330/t). Average temperatures span from cold (e.g., Edmonton 3.1℃) to hot/humid (e.g., Miami 24.6℃, 72.5% humidity). These parameters are central inputs to TEA and scenario assessments.

---

[37] Japan Oil, Gas and Metals National Corporation (JOGMEC) (2025) LNG price trends. Available at: https://oilgas-info.jogmec.go.jp/nglng/1007905/1010531.html (Accessed: 21 August 2025).

[38] GlobalPetrolPrices.com (n.d.), "Natural gas prices", https://www.globalpetrolprices.com/natural_gas_prices/ (Retrieved November 7, 2022)

[39] U.S. Energy Information Administration (EIA) (2024) *U.S. natural gas prices have declined as supply increased in 2024.* Available at: https://www.eia.gov/todayinenergy/detail.php?id=64344 (Accessed: 10 September 2025).

[40] Japan Science and Technology Agency (JST) (2019) *A study toward the social implementation of evaluation methods based on life cycle thinking（FY2019）* Japan Science and Technology Agency. Available at: https://www.jst.go.jp/lcs/pdf/fy2019-pp-07.pdf (Accessed: 21 August 2025).

[41] Trading Economics (n.d.) Japan economic indicators. Available at: https://jp.tradingeconomics.com/ (Accessed: 10 September 2025).

Table 2: Regional parameters for techno-economic assessment

		Japan		Australia			Canada			United States	
Paramater	**Unit**	**Tomakomai**	**Fukuoka**	**Traralgon**	**Moomba**	**Millmerran**	**Edmonton**	**Estevan**	**Sarnia**	**El Paso**	**Miami**
Electricity (Renewable Energy)	$/kWh	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
Fuel Gas	$/t	**584**	**584**	**374**	**394**	**378**	**152**	**142**	**167**	**161**	**161**
Industrial Water	$/t	**0.15**	**0.12**	**2.38**	**2.16**	**2.26**	**4.07**	**2.03**	**0.58**	**1.30**	**0.91**
CaCO3	$/t	**250**	**250**	**250**	**250**	**250**	**250**	**250**	**250**	**250**	**250**
KOH	$/t	**700**	**700**	**700**	**700**	**700**	**700**	**700**	**700**	**700**	**700**
Labor Cost	M$/y	**0.28**	**0.28**	**0.58**	**0.58**	**0.58**	**0.46**	**0.46**	**0.46**	**0.57**	**0.57**
Unit land cost	$/m2	**121**	**930**	**1**	**0**	**1**	**1**	**1**	**4**	**0**	**0**
Carbon Credits	$/t	**200**	**200**	**272**	**272**	**272**	**330**	**330**	**330**	**272**	**272**
Discount Rate	%	**5%**	**5%**	**8%**	**8%**	**8%**	**9%**	**9%**	**9%**	**7%**	**7%**
Federal and State tax rate	%	**23%**	**23%**	**30%**	**30%**	**30%**	**27%**	**27%**	**27%**	**22%**	**27%**

4.2.2. Process Simulation

Process simulations for the selected ten regions were conducted using Aspen Plus[29]. Carbon Engineering's DAC technology[28] has already disclosed detailed operating conditions, and in this technical study report, independent process simulations were performed with reference to those published results. Further details are available in previously published studies[42].

In this case study, the Aspen Plus process simulation covers the DAC capture island from the air contactor through the pellet reactor/calciner/slaker and up to the CO_2 pretreatment section (cooling/washing), i.e., a plant-gate boundary at the outlet of the pretreatment section. Accordingly, the CO_2 Compressor Section and downstream processes (CO_2 compression, conditioning beyond pretreatment, transport, geological storage, and associated leakage/MRV) are not modeled in the process simulation and are excluded from the reported LCA/TEA results. Electricity supply is assumed to be provided by renewable electricity (on-site and/or externally supplied), and therefore the Gas Turbine Generator Section is not included. The reported indicators (e.g., $\boldsymbol{RM_{PJ}}$, $\boldsymbol{RM_{air}}$, $\boldsymbol{CR_{air}}$, and the levelized cost) should be interpreted as plant-gate results conditional on downstream CO_2 compression/transport/storage; when reporting full-chain net CO_2 removal, downstream emissions and leakage should be added consistently with the common methodology boundary (Figure 3).

(1) Process Simulation Conditions

CO_2 Capture Conditions

- **Capture factor**: 172.5 t/h as CO_2 (CO_2 captured from ambient air: 120.3 t/h)
- **Pressure**: Atmospheric pressure (0.1 MPa)
- **Temperature**: Dependent on the operating conditions of the Water Knockout Drum (36–71 °C)

Air Conditions

- **Temperature**: Annual average temperature at each of the ten locations
- **Pressure**: Atmospheric pressure
- **Relative humidity**: Annual average relative humidity at each of the ten locations
- **Air composition**:

  CO_2: 400 ppmv (dry basis)

---

[42] Morimoto, S., Kitagawa, N., Bensebaa, F., Kumar, A., Kataoka, S. and Taniguchi, S. (2023) Scenario assessment of introducing carbon utilization and carbon removal technologies considering future technological transition based on renewable energy and direct air capture. Journal of Cleaner Production, 402, 136763. https://doi.org/10.1016/j.jclepro.2023.136763

O_2: 23.0 % vol. (dry basis)

N_2: 75.96 % vol. (dry basis)

Other Conditions

- **Fuel**: 100% Methane
- **Cooling water**: 32 °C supply / 37 °C return
- **Oxygen supply**: Oxygen produced by air separation

  O_2: 95.6 vol.%

  N_2: 4.4 vol.%
- **Water supply**: Industrial water

  Temperature: 25 °C

In this technical study report, the supplied electricity is assumed to be provided by on-site power generation and externally supplied renewable energy.

(2) Process Description

The process configuration is described below.
The DAC process consists of the following four main sections:

① **Air Contactor Section**
② **Calciner Section**
③ **Slaker Section**
④ **CO_2 Pretreating Section**

The scope of the process simulation was limited to CO_2 separation and capture. Accordingly, the CO_2 Compressor Section and the Gas Turbine Generator Section (not required due to the use of renewable energy) were excluded. The fixation of CO_2 from ambient air comprises the following processes.

(2.1) Air Contactor Section

CO_2 in ambient air is absorbed in the Air Contactor using 2N aqueous KOH solution, forming potassium carbonate as K_2CO_3:

$$CO_2(g) + 2KOH \rightarrow H_2O + K_2CO_3 - 95.8kJ/mol \tag{29}$$

The absorbent solution is circulated through the Air Contactor by a circulation liquid pump, and the absorbed CO_2 is returned to the Pellet Reactor.

(2.2) Pellet Reactor Section

In the Pellet Reactor, K_2CO_3reacts with supplied $Ca(OH)_2$ to produce $CaCO_3(s)$ and regenerate KOH. $CaCO_3(s)$ crystallizes and settles at the bottom of the reactor:

$$K_2CO_3 + Ca(OH)_2 \rightarrow 2KOH + CaCO_3(s) \qquad (30)$$

The Pellet Reactor operates as a solid–liquid fluidized bed, where reaction (30) and $CaCO_3$ crystallization occur simultaneously. The circulating liquid is withdrawn from the top of the reactor and fed to a Fines Filter (F-01), where the grown $CaCO_3$ crystals are separated from the circulating liquid. The filtered circulating liquid (aqueous KOH solution) is returned to the bottom of the Pellet Reactor by a Filter Transfer Pump to promote $CaCO_3$ crystallization and establish the circulation system required to maintain the fluidized bed.

A mixture of circulating liquid equivalent to the $Ca(OH)_2$ feed and $CaCO_3(s)$ overflows from the top of the Pellet Reactor and flows to $CaCO_3$ Wash Tank. $CaCO_3$ is reported to be in a relatively filterable form.

The circulating liquid is also supplied to the Air Contactor to fix CO_2 from ambient air. The solution supplied to the Air Contactor is continuously circulated, withdrawn, and returned to the Pellet Reactor.

(2.3) Calciner Section

In the Calciner, $CaCO_3(s)$ dried in the downstream Slaker Section is calcined using high-temperature combustion gas, converting it to CaO and releasing CO_2:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g) + 178kJ/mol \qquad (31)$$

Methane is combusted with pure oxygen, and $CaCO_3$ is decomposed at approximately 900 °C. After heat recovery, the CO_2 is washed and cooled using industrial water supplied to the facility. The Calciner is operated as a fluidized bed to enhance gas–solid contact. While both dense-bed and fast-bed configurations are commonly applied, a fast-bed system was selected in this study to achieve high gas velocities.

A solid circulation flow between a fluidized bed and a cyclone, widely used in the cement industry for limestone calcination, is also adopted in Carbon Engineering's DAC technology[28].

(2.4) Slaker Section

In the Slaker, CaO from the Calciner reacts with moisture carried over with wet $CaCO_3$ from the Pellet Reactor, producing $Ca(OH)_2$:

$$CaO(s) + H_2O(l) \rightarrow Ca(OH)_2 - 63.9kJ/mol \qquad (32)$$

An amount of water equivalent to the carryover moisture is circulated using a Slaker Blower to form a fluidized bed, promoting drying and reaction. As in the Calciner, a fast-bed fluidized configuration is adopted, and sufficient gas velocity for fast-bed operation is achieved by the Slaker Blower capacity.

As shown in reaction (32), the slaking reaction is exothermic, and the released heat is recovered by generating 4.2 MPa steam in a Slaker Steam Generator. A BEU-type shell-and-tube heat exchanger, stabbed into the Slaker vessel (with only the tube bundle inserted into the shell), was adopted.

$Ca(OH)_2$ produced in the Slaker is cooled in a Lime Cooler, where heat is recovered to boiler feedwater, and then sent to the Quick Lime Mix Tank, where a $Ca(OH)_2$ slurry is prepared. This slurry is supplied to the Pellet Reactor and consumed for regenerating KOH from K_2CO_3.

The Lime Cooler recovers heat from hot solids (~300 °C) to high-pressure water (4.2 MPa). In this technical study report, a vertical BEM-type heat exchanger with four stacked stages was assumed, with $Ca(OH)_2$ slurry on the tube side and 4.2 MPa boiler feedwater on the shell side. BEM-type exchangers have proven applicability to high-pressure water and pose no structural design issues.

$CaCO_3$ discharged from the Pellet Reactor is sent to $CaCO_3$ Wash Tank, where it is washed with circulating water and make-up water.

(2.5) CO_2 Pretreating Section

CO_2 gas from the Calciner, at approximately 370 °C, is sent to the Wash Water Tank, where it is cooled by direct contact with externally supplied water. The amount of supplied water is determined by the overall water balance of the facility, and therefore cooling is limited to near-ambient temperatures. Simulation results indicate that cooling to 38–71 °C is achievable.

The cooling water discharged from the bottom of the Wash Water Tank is transferred using a gravity-driven configuration.

4.2.3. LCA/TEA Methodology for Case Study

The results of the estimated energy consumption, utility consumption, and equipment costs for the ten regions, derived from the process simulation results, are summarized in Table 3.

Table 3: Results of process simulation

		Japan		Australia			Canada			United States	
Result	**Unit**	**Tomakomai**	**Fukuoka**	**Traralgon**	**Moomba**	**Millmerran**	**Edmonton**	**Estevan**	**Sarnia**	**El Paso**	**Miami**
External Power Input	kWh/h	**19,059**	**18,183**	**18,305**	**17,933**	**18,332**	**19,928**	**19,655**	**18,813**	**18,831**	**17,615**
Fuel Gas	t/h	**14**									
Industrial Water	t/h	**318**	**379**	**381**	**890**	**544**	**364**	**381**	**362**	**828**	**277**
CaCO3	t/h	**3.40**									
KOH	t/h	**0.07**									
Project Years	y	**20**									
Fixed Capital Investment	$	**1.74**	**1.68**	**1.74**	**1.69**	**1.68**	**1.82**	**1.82**	**1.75**	**1.72**	**1.63**
Land area	km2	**0.24**									

The LCA of DAC is conducted based on the methodology described in Chapter 3, by estimating CO_2 removal from air ($\boldsymbol{RM_{air}}$) and GHG emissions ($\boldsymbol{EM_{PJ}}$) for the ten regions. Specifically, these values are calculated by multiplying the energy consumption and utility consumption shown in Table 3 by CO_2 emission factors per unit of energy and per unit of utility and summing the results. The CO_2 emission factors are referenced from the ecoinvent database[43] and treated as secondary data. Consistent with the common LCA methodology, primary data should be prioritized for significant high-contribution items/processes identified in the system boundary (e.g., electricity/heat production, capture steps, and specific chemicals); where primary data are unavailable, relevant secondary data may be used with appropriate disclosure.

Similarly, TEA is conducted based on the methodology described in Chapter 3 to estimate the levelized cost of CO_2. Specifically, the cost is calculated using the unit prices and economic parameters listed in Table 2, together with the energy consumption, utility consumption, equipment costs, and land area shown in Table 3.

---

[43] ecoinvent Association (n.d.) ecoinvent database. Available at: https://ecoinvent.org/

5. Assessing the Potential of CO_2 Removal and Economic Viability for DAC at Country and Regional Levels

In this chapter, using the country- and region-specific datasets prepared in Chapter 4, together with process simulation results obtained under a common LCA/TEA methodology, the feasibility of DAC deployment at both national and regional levels is comparatively assessed. The assessment focuses on two key dimensions: environmental effectiveness, represented by the net CO_2 removal potential, and economic performance, represented by the levelized cost of CO_2 removal.

As a case study, primarily targeting countries participating in MI CDR Mission, ten sites across four countries are selected. A representative KOH-based DAC process (Carbon Engineering type[28]) is simulated using Aspen Plus[29], and the process performance is evaluated in terms of process flow characteristics, energy and material consumption, CO_2 emissions, heat balance, CAPEX, OPEX, and land area requirements. Differences in meteorological conditions, particularly average temperature and humidity, are explicitly incorporated as siting parameters, as they directly affect CO_2 recovery efficiency and power consumption.

5.1. Indicators and Evaluation Framework Linking LCA/TEA

On the LCA side, the assessment scope includes upstream life-cycle emissions associated with energy and material inputs, utilities (electricity and heat), chemicals, water supply and wastewater treatment, and waste management. Consistent with the methodology described in Chapter 3, priority is given to the collection of primary data for processes with high contributions, such as electricity and heat supply, the CO_2 capture step, and specific chemicals. This framework enables a consistent comparison of net CO_2 removal, defined as CO_2 removed from air minus total life-cycle CO_2 emissions, rather than focusing solely on the gross captured amount.

On TEA side, the principal indicator is the levelized cost of CO_2 removal. CAPEX and OPEX are estimated within a standardized costing framework, while site-specific unit prices (electricity, fuel, water, chemicals, and labor) and institutional conditions (e.g., taxation and policy incentives) are explicitly reflected. This allows for a consistent comparison of economic performance across countries and regions.

In this case study, net results are reported on a plant-gate basis (excluding downstream compression/transport/storage), consistent with the process-simulation boundary described in Chapter 4.2.2. Full-chain net removal would require adding downstream emissions and leakage per Figure 3.

5.2. Life-Cycle CO_2 Perspective on Effective Removal

This section summarizes the net CO_2 removal performance of DAC from a life-cycle perspective (Figure 5), based on the balance between CO_2 removed from air and associated life-cycle CO_2 emissions.

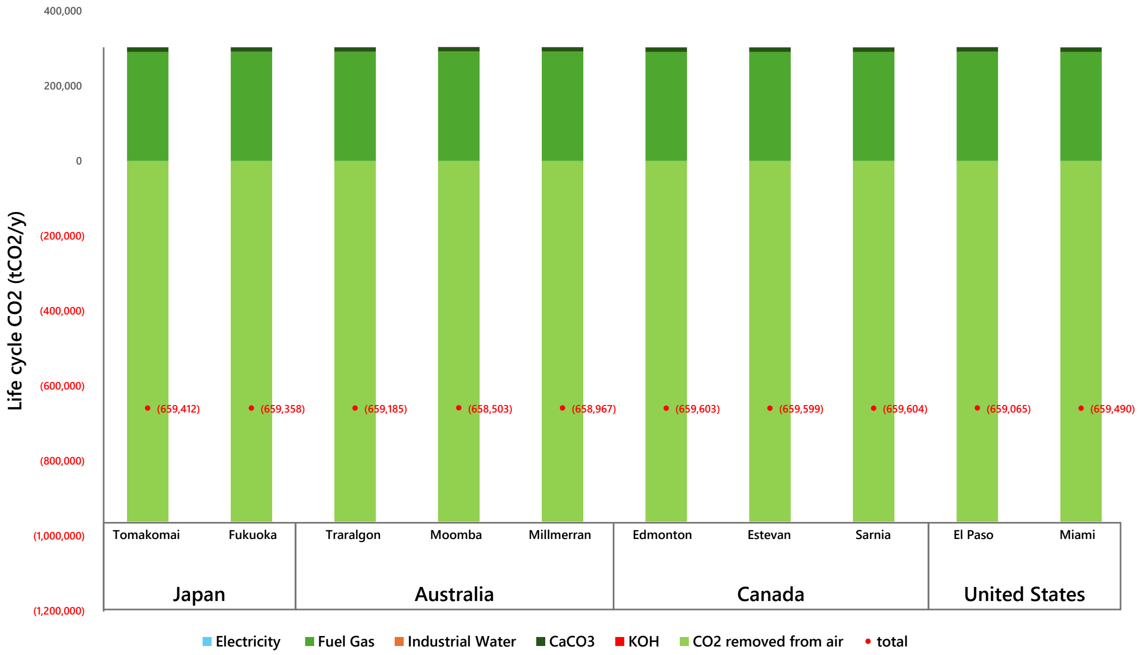


Figure 5 Result of Life-Cycle CO_2 (tCO2/y)

For each site, the CO_2 removed from air and the corresponding life-cycle emissions—attributed to electricity, fuel gas, industrial water, $CaCO_3$, KOH, and other inputs—are presented within a single figure. This representation enables a direct comparison across sites using a common decomposition axis, clarifying the relationship between the gross capture amount and the life-cycle emission penalty.

A critical point in interpreting these results is that net CO_2 removal is defined as the captured CO_2 minus life-cycle emissions. The carbon intensity of energy, particularly electricity and heat, plays a dual role:

(i) it reduces the net removal amount through increased life-cycle emissions, and
(ii) it simultaneously increases operating costs.

Accordingly, access to low-carbon electricity and the selection of appropriate heat sources are directly linked to achieving both high net CO_2 removal effectiveness and favorable economic performance.

In addition to the site-level comparison, the results are aggregated at the country level to identify national trends in net CO_2 removal. When consolidating multiple sites within each country, the net removal performance is found to be strongly dependent on the carbon intensity of the national energy system. Countries with greater availability of low-carbon electricity exhibit smaller life-cycle emission penalties and consequently higher net CO_2 removal. At the same time, variability among sites within the same country remains due to differences in meteorological conditions and regional electricity mixes. These findings indicate that both national-level energy and institutional conditions and regional siting factors must be jointly considered when assessing the effectiveness of DAC deployment.

In cold regions, ambient conditions may impose operational constraints that are not fully captured by annual-average temperature/humidity inputs; such limitations should be documented as interpretation notes and, where feasible, addressed via scenario/sensitivity analysis incorporating location conditions.

5.3. Levelized Cost of CO_2 and Key Cost Drivers

The levelized cost of CO_2 removal is compared across sites, with cost components disaggregated into Electricity, Fuel Gas, Industrial Water, $CaCO_3$, KOH, Labor, CAPEX, and tax. The results are summarized in Figure 6.

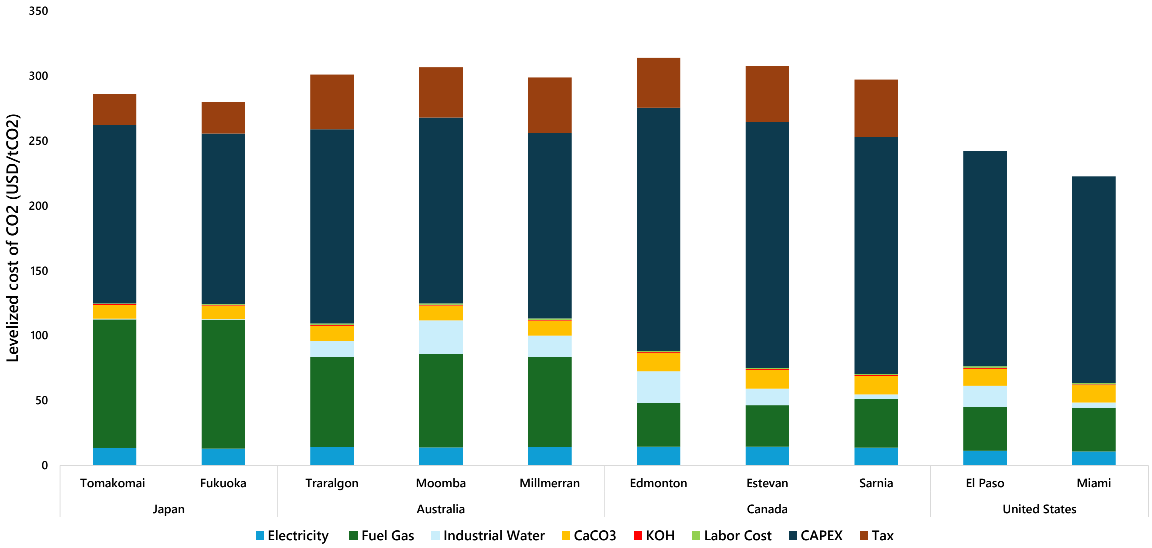


Figure 6 Result of Levelized cost of CO2 (USD/tCO2)

This breakdown enables a detailed discussion of:

- which cost items drive regional differences,

- how policy and market conditions—such as energy prices, labor costs, capital costs, and raw material prices, and taxation—affect overall economics, and
- which levers are most effective for technology improvements (e.g., energy efficiency and reduced chemical consumption) and supply-chain strategies (e.g., procurement and site selection).

For the common case study assuming a capture scale of 120.3 t-CO_2/h, the results indicate that Fuel Gas and CAPEX constitute the largest portions of the levelized cost across all sites, while Electricity and Industrial Water show more site-dependent variability. In addition, Tax assumptions materially affect cross-country comparability, which highlights that sites in jurisdictions assumed to have zero or favorable taxation (e.g., via specific incentives) show a clear cost advantage.

Furthermore, cross-site comparisons that explicitly reflect institutional conditions (taxation and policy incentives) show that differences in these parameters can significantly influence the economic attractiveness of DAC alongside technical parameters. In particular, sites with lower taxation assumptions and favorable policy incentives exhibit lower overall levelized costs relative to locations with comparable technical performance but higher tax burdens.

5.4. Implications for National and Regional Deployment Strategies

By integrating the two evaluation dimensions—life-cycle CO_2 removal effectiveness and levelized cost—the assessment of suitable locations for DAC deployment at national and regional levels must satisfy several key criteria. First, because temperature and humidity affect CO_2 recovery efficiency and power demand, siting conditions must be explicitly incorporated as process inputs to capture performance variability. Second, regional differences in high-contribution items such as energy, water, and chemical supply propagate to both net removal effectiveness and economic performance.

Therefore, priority improvement areas— fuel/heat procurement and efficiency improvements, capital cost reduction, water sourcing and consumption management, and the strategic use of policy incentives and tax design—should be systematically identified based on itemized breakdowns. This approach enables not only an evaluation of whether DAC costs are high or low in each region, but also a clear explanation of which conditions act as bottlenecks and what changes would most effectively improve deployability at the national and regional levels.

6. Conclusion · Action Plan

This technical study report addresses the challenge that, in cross-border DAC project evaluations, differences across studies in "scope/system boundaries/assumptions/metrics" undermine comparability. To resolve this, it defines a harmonized LCA/TEA methodology and demonstrates that it can be applied across multiple countries and sites, enabling credible comparisons by aligning system boundaries, data priorities, and evaluation criteria.

On the LCA side, the common guideline emphasizes transparent boundary setting—from upstream emissions through plant construction, utilities (electricity/heat), chemicals, CO_2 capture, and waste streams—and prioritizes primary data collection for key high-contribution items/processes (e.g., electricity/heat, capture steps, and specific chemicals). It also requires disclosure of electricity/heat production mixes, final CO_2 output concentration, capture efficiency, and the fate of CO_2 from both chemicals and fossil energy used for utilities, to ensure robust accounting of net performance.

On the TEA side, the methodology standardizes CAPEX estimation starting from TPEC and harmonizes OPEX categorization and cashflow treatment while explicitly reflecting site-specific unit prices and institutional conditions (including taxation and policy incentives). This standardized structure enables site-to-site and scenario-to-scenario comparison on a consistent basis.

In the 10-location case study applying the common methodology, ambient conditions (temperature and humidity), energy and water prices, CAPEX levels, and institutional parameters (tax and incentives) materially affected both performance and cost. Consistent with the levelized-cost breakdown, fuel gas and CAPEX are dominant cost drivers, while electricity, industrial water, and tax assumptions contribute to site-specific differences. These findings underscore the importance of maintaining location-specific input datasets and conducting sensitivity analysis when prioritizing DAC deployment options.

Action Plan

Drawing on the findings of this technical study report, the following items are set forth as an action plan. The actions enumerated herein do not represent the intentions of MI CDR Mission; rather, they reflect the outcomes of the survey and study and identify measures deemed necessary for implementation.

- Institutionalize operation of the common LCA/TEA guideline to secure comparability by ensuring a shared evaluation baseline (aligned boundaries, metrics, and data-priority rules) across countries, organizations, and projects.
- Expand primary data collection and enhance transparency for major high-contribution items/processes (electricity/heat, capture steps, key chemicals), including disclosure of electricity/heat production mixes, to improve the accuracy of net CO_2 removal accounting.
- Continuously update country/region datasets (prices, policy instruments, climate parameters) and maintain them as comparable TEA inputs.
- Standardize evaluation and sensitivity and uncertainty analysis that explicitly incorporates location conditions (temperature/humidity), including consideration of constraints in cold regions.
- Establishment of a harmonized methodology for uncertainty analysis and integrate it into the common LCA/TEA framework. This includes conducting a review of existing uncertainty analysis methodologies[18] and their application to provide a more robust assessment of both environmental and economic outcomes.
- As a next step, extend the common LCA/TEA methodology beyond DAC to related CDR pathways (e.g., enhanced rock weathering), while continuing country-specific data collection to support integrated multinational assessments.

Appendix 1: Literature review with the past survey

1. Introduction

This Appendix provides a detailed review of methodologies and calculation examples from various publications, based on a literature survey on DAC technologies conducted by METI in fiscal year 2023. The review focuses on international guidelines and key literature related to LCA/TEA for DAC, with particular attention to the harmonization of functional units, system boundaries, emission scopes, and comparability issues.

In this technical study report, the advanced case example of LCA for DAC is DOE's "Best Practices for LCA of DACS[Article 24]," which is widely referenced in technical publications and demonstration projects. This Appendix investigates the functional-unit calculation formula within the DOE methodology and compares it with the results of the literature survey.

International best practice in LCA for DAC is to use the "mass of CO_2 captured from the atmosphere and permanently stored" as the functional unit, and to adopt a "cradle-to-grave" system boundary including permanent geological storage. This approach is consistent with ISO 14040[9]/14044[10] and is widely adopted in key international guidelines and literature. The distinction between gross and net removal, and the explicit treatment of co-products and avoided emissions, are also important for comparability and interpretation.

In this Appendix, the DOE guideline and major international literature are referenced to clarify the harmonization of functional units, system boundaries, and reporting methods for DAC LCA, and to provide a basis for consistent and internationally comparable LCA implementation and interpretation.

2. List of DAC-related articles reviewed

The following table shows the literature survey from past years that was referenced in this additional investigation. The results of the literature survey from past years are also shown at the end of this technical study report.

Table 4; List of DAC-related Articles

No.	Year	Author	Title
Article 1	2011	**House, K.Z. et al.**	Economic and energetic analysis of capturing CO2 from ambient air
Article 2	2014	**Zeman, F.**	Reducing the Cost of Ca-Based Direct Air Capture of CO2
Article 3	2016	**Fasihi, M. et al.**	Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants
Article 4	2017	**Fasihi, M. et al.**	Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe-Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World
Article 5	2017	**van der Giesen, C. et al.**	A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO2 versus MEA-Based Postcombustion Capture
Article 6	2018	**Keith, D.W. et al.**	A Process for Capturing CO2 from the Atmosphere
Article 7	2018	**Daggash, H.A. et al.**	Closing the carbon cycle to maximise climate change mitigation: power-to-methanol vs. power-to-direct air capture
Article 8	2018	**de Jonge, M.M.J. et al.**	Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents
Article 9	2019	**Breyer, C. et al.**	Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation
Article 10	2019	**Realmonte, G. et al.**	An inter-model assessment of the role of direct air capture in deep mitigation pathways
Article 11	2019	**Fasihi, M. et al.**	Techno-economic assessment of CO2 direct air capture plants
Article 12	2019	**Creutzig, F. et al.**	The mutual dependence of negative emission technologies and energy systems
Article 13	2019	**Breyer, C. et al.**	Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling
Article 14	2020	**Kiani, A. et al.**	Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process
Article 15	2020	**Becattini, V. et al.**	Role of Carbon Capture, Storage, and Utilization to Enable a Net-Zero-CO2-Emissions Aviation Sector
Article 16	2020	**Sadiq, M.M. et al.**	A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks

Article 17	**2020**	**Liu, C.M. et al.**	A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production
Article 18	**2020**	**McQueen, N. et al.**	Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States
Article 19	**2021**	**Kosaka, F. et al.**	Enhanced Activity of Integrated CO2 Capture and Reduction to CH4 under Pressurized Conditions Towards Atmospheric CO2 Utilization
Article 20	**2021**	**Deutz, S. & Bardow, A.**	Life cycle assessment of an industrial direct air capture process based on temperature-vacuum swing adsorption
Article 21	**2021**	**Terlouw, T. et al.**	Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources
Article 22	**2021**	**Terlouw, T. et al.**	Life cycle assessment of carbon dioxide removal technologies: a critical review
Article 23	**2021**	**Madhu, K. et al.**	Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment
Article 24	**2022**	**Cooney, G.**	BEST PRACTICES FOR LIFE CYCLE ASSESSMENT (LCA) OF DIRECT AIR CAPTURE WITH STORAGE (DACS)
Article 25	**2022**	**Galimova, T. et al.**	Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals
Article 26	**2022**	**Wang, J. et al.**	Energetic and Life Cycle Assessment of Direct Air Capture: A Review
Article 27	**2022**	**Qiu, Y. et al.**	Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100
Article 28	**2023**	**Mertens, J. et al.**	Carbon capture and utilization: More than hiding CO2 for some time
Article 29	**2025**	**Glaser, M. et al.**	How do ambient conditions influence sorbent selection in adsorption-based direct air capture?

3. Functional Unit and Emission Scope Harmonization (Cross-Study Comparison between DOE's best practice of LCA of DACS)

3.1. Functional Unit Denominator Differences (per t-CO_2 captured vs per t-CO_2 removed vs product-based FU, etc.)

In the DOE guideline[Article 24,] the recommended functional unit for LCA is the "mass of CO_2 captured from the atmosphere and permanently stored." This approach emphasizes using the "amount of CO_2 that is of atmospheric origin and permanently stored geologically" as the denominator, rather than simply the "amount of CO_2 captured." The rationale is to clarify the essential function of DACS as CDR technology and to facilitate comparison with other CDR and DACS technologies. DOE also specifies that CO_2 should be pressurized to 2,200 psig and have a purity of at least 95%.

Furthermore, reporting the "net mass of CO_2e captured from the atmosphere and permanently stored" is recommended. The system boundary should be cradle-to-grave, including permanent geological storage of CO_2. While other functional units such as "mass of CO_2 captured from air" or "net CO_2e removed" are sometimes used, DOE recommends "mass of CO_2 captured from the atmosphere and permanently stored" as the standard for DACS LCA. Example calculations and equations for different functional units are provided, illustrating how the choice of denominator affects the interpretation of results:

$\boldsymbol{a}$: Emission of Supply Chain from Consumables and Non-consumables
$\boldsymbol{b}$: Uncaptured on-site fossil from DAC Process
$\boldsymbol{c}$: Captured atmospheric (Net) to DAC process / Process to CO_2 transport and subsurface Storage
$\boldsymbol{d}$: Captured on-site fossil to CO_2 transport and subsurface Storage
$\boldsymbol{e}$: Total Captured (atmospheric+fossil)
$\boldsymbol{f}$: Downstream supply chain + operations + leakage
$\boldsymbol{g}$: Co-product cradle-to-gate

Mass of CO_2 captured:

$$\boldsymbol{kgCO_2e = \frac{a+b+c}{c;d} = \overset{c=1}{\frac{0.40+0.05-1.00}{1.00+0.50}} = -0.37} \tag{1}$$

Mass of CO_2 captured from the atmosphere:

$$c = 1$$

$$kgCO_2e = \frac{1+b-c+f}{c} = -0.55 \tag{2}$$

Mass of CO_2 captured from the atmosphere and permanently stored:

$$c = 1$$

$$khCO_2e = \frac{a+b-c+f}{C} = \frac{0.40+0.05-1.00+0.01}{1.00} = --0.54 \tag{3}$$

Mass of net CO_2e captured from the atmosphere and permanently stored:

$$Scale\ up\ factor\ C' = \frac{-1}{FU\ 3\ Result} = \frac{-1}{-0.54} = 1.85$$

$$kgCO_2e = \frac{c'(a+b+f)-c'}{1} = \frac{0.85-1.85}{1} = -1 \tag{4}$$

Among these, (3) is recommended for LCA of DACS. This is to accurately reflect the essential function of DACS as CDR and is consistent with international LCA standards (ISO 14040[9]/14044[10]) and other key literature.

In comparison with other literature, Deutz and Bardow (2021) [Article 20] use "1 kg CO_2 captured around ambient conditions with a purity above 99%" as the functional unit, evaluating both cradle-to-gate (up to CO_2 capture) and cradle-to-grave (up to geological storage).

Terlouw et al. (2021) [Article 21] also use "gross removal of 1 ton CO_2 from the atmosphere via the use of a DAC plant combined with geological CO_2 storage" as the functional unit. de Jonge et al. (2019)

Article 8 use "1 t of CO_2 stored" as the functional unit, evaluating the entire process from capture to geological storage.

These key publications, similar to DOE, design their functional units with the "mass of CO_2 of atmospheric origin that is permanently stored" as the denominator, which is consistent with international best practices. On the other hand, for cases involving CO_2 utilization (Carbon Capture and Utilization), such as for fuels or chemicals, the "amount of product generated (e.g., 1 MJ of fuel)" is generally used as the functional unit in LCA. This is because the comparison in LCA is made between processes that fulfill the same function (e.g., energy supply, chemical supply), such as fossil fuel-derived fuels or biofuels. For example, the GHG emissions for "production and combustion of 1 MJ of synthetic fuel" are compared.
In contrast, for DACS as CDR, the standard is to use the "amount of CO_2 removed" as the functional unit (e.g., 1 tCO_2). This is because the main function of CDR technologies is to remove CO_2 from the atmosphere and permanently sequester it.
Selected literatures describe the following:

- Keith et al. (2018) [Article 6] uses "1 t-CO_2 removed" as the functional unit for LCA in DACCS applications, and "1 MJ fuel" for CCU applications (fuel synthesis, etc.)
- Fasihi et al. (2019) [Article 11] evaluates DACCS (CDR) using "1 t-CO_2 removed" as the functional unit for cost and LCA, and for CCU, evaluates using the amount of product (e.g., 1 MJ fuel, 1 kg chemical)
- van der Giesen et al. (2017) [Article 5] and Liu et al. (2020) [Article 17] use "1 tCO_2 removed" for DACCS and "1 MJ fuel" or "1 kg chemical" for CCU as the functional unit.

3.2. Functional Unit Numerator / Accounted Flows (gross vs net; what is subtracted/credited)

For functional unit numerator and accounted flows, the DOE guideline[Article 24] has been adopted by many key DAC-related articles, and high consistency is observed in the definitions of the numerator and denominator, the treatment of gross/net, the handling of subtraction/credits, and unit consistency.

In the DOE guidelines, the numerator is “the total GHG emissions (CO_2e) occurring across the system,” encompassing all emissions within the system boundary, including operation and construction of the DAC facility, raw materials, energy supply, CO_2 compression, transport, storage, and waste management. The denominator is “the mass of CO_2 removed from the atmosphere and stored.” Gross removal is defined as “the total amount of CO_2 captured from air and stored,” and net removal is defined as “gross removal minus the system-wide GHG emissions (numerator)." The calculation is as follows:

$$\boldsymbol{Net\ CO^2 removal\ =\ CO^2 removed\ from\ air\ (denominator) - \ GHG\ emissions\ (numerator)}$$

Both the numerator and denominator are expressed consistently in "kg CO_2" or "t-CO_2," ensuring unit consistency. DOE emphasizes "net CO_2 removal" and recommends using LCA indicators such as "kg CO_2e emitted per kg CO_2 removed" and "kg CO_2e removed per kg CO_2 captured and stored." The guidelines also explicitly address the definition of system boundaries, the treatment of credits and by-products, differences in functional units depending on the fate of captured CO_2 (storage or utilization), and co-product management (in accordance with ISO 14044[10]).

In related comparative literature, the numerator is likewise taken as "system-wide GHG emissions (CO_2e)," and the denominator as "the quantity of CO_2 captured from air and stored," with gross removal defined as "the total CO_2 captured and stored," and net removal as "gross removal minus system-wide GHG emissions." Many publications employ indicators aligned with DOE, such as "net CO_2 removal" and "carbon removal efficiency (net removal efficiency)." With respect to subtraction/credits, net removal is generally calculated by subtracting energy-related emissions (CO_2 emissions from electricity and thermal sources). The treatment of by-products and co-products adheres to ISO 14044, and some studies employ system expansion or allocation. Unit consistency is also maintained, unified as "kg CO_2" or "t-CO_2," in line with the DOE guidelines.

Terlouw, T. et al. (2021) [Article 21] and Wang, J. et al. (2022) [Article 26] reveal methodological differences in the handling of by-products and co-products (e.g., use of system expansion versus allocation), and identify cases where credits (emission reductions attributable to by-products) are aggregated into "net removal." For example, in LCAs of biochar or BECCS, system expansion (substitution) may be used, and avoided emissions may be added as "negative emissions." In contrast, the DOE guidelines stipulate a clear distinction between "physical removal from the atmosphere" and "avoided emissions."

Terlouw, T. et al. (2021) [Article 21] point out that many LCAs do not distinguish between "avoided emissions" and "negative emissions (removal from the atmosphere)," instead combining them. The DOE guidelines recommend managing co-products according to the ISO 14044[10] hierarchy (subdivision → system expansion → allocation) and require separate reporting of avoided emissions and atmospheric removal.

Regarding the treatment of gross/net, Wang, J. et al. (2022) [Article 26] note that some studies assess only gross removal and do not explicitly distinguish net removal (i.e., gross minus system-wide GHG emissions). The DOE guidelines recommend an explicit distinction between gross and net and place emphasis on net removal.

3.3. Emission Scope Mapping (direct / indirect / embodied; inclusion of transport & storage; end-use pathways)

DOE[Article 24] explicitly defines the following emission scopes for DACS LCAs and recommends a comprehensive assessment:

- Direct emissions: Emissions occurring during operation of the DAC facility (e.g., fuel combustion, process emissions).
- Indirect emissions: Emissions from the generation of purchased electricity and heat, and emissions from the manufacturing of raw materials and chemicals.
- Embodied emissions: Emissions associated with the construction of the plant, equipment, and infrastructure, and with end-of-life management. These may be omitted in initial screening assessments but are required for detailed assessments and for large-scale deployment.
- CO_2 transport, compression, and storage: Emissions associated with CO_2 compression, pipeline transport, geological storage, and MRV (monitoring, reporting, and verification).
- Waste management: Emissions associated with sorbent/solvent disposal and other waste handling.
- Emission factors for renewable energy: Use emission factors based on the actual grid mix, or if supplied by renewables, values from LCA databases.

Detailed analysis of embodied emissions:
Embodied emissions refer to greenhouse gas emissions arising from the manufacturing, installation, and end-of-life (disposal/recycling) of the DAC system's construction, equipment, and infrastructure. While the DOE guidelines[Article 24] allow omission in early-stage evaluations, they state that embodied emissions must be considered in detailed assessments and for large-scale deployment. This is because, as DAC is scaled up, emissions related to production, transport, installation, and disposal of construction materials (e.g., concrete, steel, aluminum, copper, plastics) and equipment (e.g., adsorption columns, fans, heat pumps, batteries) become non-negligible contributors to the overall GHG footprint.

In practice, the part of LCA studies such as Deutz & Bardow (2021) [Article 20] and Terlouw et al. (2021) [Article 21] evaluate embodied emissions from DAC plant construction, equipment, and infrastructure in detail. For example, Deutz & Bardow (2021) Article 20 estimate embodied emissions for a 4 kt CO_2 per year DAC plant at 15 g CO_2e per kg CO_2 without recycling and 6 g CO_2e per kg CO_2 with metal recycling, showing that when clean electricity is used the relative contribution of embodied emissions increases. Principal sources include concrete and steel for foundations and buildings, metals in process units, and equipment such as batteries and heat pumps. At large scales, increased demand for these materials in global markets should also be considered.

Furthermore, consumables such as sorbents and solvents are part of embodied emissions. Depending on sorbent consumption rates, lifetimes, and recycling rates, their contribution to total GHG emissions may increase; therefore, LCAs should comprehensively assess sorbent manufacturing processes, feedstock sourcing, and end-of-life (disposal/recycling) stages.

Relationship with other scopes and comparison with literature
LCA studies published since 2019 (e.g., Deutz & Bardow Article 20; Terlouw et al. Article 21) cover the DOE guideline scopes (direct, indirect, and embodied emissions; CO_2 transport and storage; waste management; and end use) almost comprehensively. By contrast, studies published before 2018 or early-stage technical assessments often consider construction and equipment embodied emissions, CO_2 transport and storage, and waste management only to a limited extent. In particular, House et al. (2011) Article 1 and Zeman (2014) Article 2 evaluate operational energy use and CO_2 compression but do not include embodied emissions from construction and equipment.

Regarding emission factors for renewable energy, DOE recommends that emission factors for purchased electricity and heat be based on the actual grid mix or values from LCA databases, and that life-cycle emissions associated with renewable electricity (e.g., from construction and end-of-life of generation assets) not be set to zero but explicitly evaluated. Deutz & Bardow (2021) Article 20 and Terlouw et al. (2021) Article 21 likewise evaluate renewable electricity emission factors using LCA database values.

3.4. Implications for Comparability and Interpretation

The DOE guideline Article 24 underscores the following points regarding LCA comparability and interpretation. First, clearly defining the goal and scope of the LCA—such as the functional unit, system boundary, and the definition of comparative systems—is deemed essential for meaningful comparisons across different DACS technologies and other CDR technologies. In particular, the guidelines recommend using “the mass of CO_2 captured from the atmosphere and permanently stored” as the functional unit and adopting a “cradle-to-grave” system boundary (from raw material extraction to final storage). These recommendations promote consistency in LCA results and enable cross-technology comparisons. The guidelines further recommend conducting sensitivity and uncertainty analyses to elucidate the influence of key parameters and assumptions on outcomes and to enhance the reliability of interpretation.

When interpreting LCA results, it is also necessary to consider trade-offs with other environmental impacts (e.g., land use, water consumption, resource use), rather than focusing solely on CO_2 removal. In addition, best practices are presented for system expansion and co-product management, aligned with ISO 14044[10] and tailored to DACS-specific challenges. Collectively, these guidelines enhance transparency, reproducibility, and comparability of LCAs and ensure consistency of interpretation in policy-making and technology selection.

Other studies likewise identify issues related to comparability and interpretation. For example, Terlouw et al. (2021) [Article 21] show that differences in functional units and system boundaries significantly affect the comparability of DACCS LCA results, and that the carbon intensity of energy sources and methodologies for co-product management (e.g., system expansion, allocation) have substantial impacts on LCA interpretation. They emphasize the importance of evaluating other environmental impacts (e.g., land-use change, water consumption, resource depletion) alongside CO_2 removal efficiency and making trade-offs explicit. The use of uncertainty and sensitivity analyses is also recommended to clarify the influence of key assumptions and parameters and to ensure the robustness of results..

Moreover, in the review by Terlouw et al. (2021) [Article 22], it is noted that clearly distinguishing "negative emissions" (removal from the atmosphere) from "avoided emissions," evaluating multiple environmental impact categories concurrently, and ensuring transparency in system boundaries and functional units are indispensable for comparability and interpretation. When applying LCA results to policy decisions or technology selection, the influence of differing assumptions and boundary conditions on interpretation should be fully considered.

Additionally, de Jonge et al. (2019)

Article 8 demonstrate that the carbon intensity of energy sources and the setting of system boundaries materially affect life-cycle carbon efficiency in DAC systems. For comparative assessments and interpretation, it is important to describe these elements explicitly and ensure transparency.

3.5. Points of Discussion

Based on the additional analysis of the past literature survey, the main points regarding LCA for DAC technologies are organized below.

- **Standardization of the functional unit and international alignment**: International best practice for DAC LCA is to use “the mass of CO_2 captured from the atmosphere and permanently stored” as the functional unit, as recommended in the DOE guidelines and key literature (Deutz & Bardow, (2021) [Article 20]; Terlouw et al., (2021) [Article 21] and de Jonge et al., (2019)

- Article 8). This facilitates comparison across other CDR technologies and among DAC technologies. In particular, evaluation within a cradle-to-grave boundary that includes permanent geological storage is required.
- **Definition of the functional unit and harmonization of indicators**: In addition to defining the functional unit for DACS, with the denominator as "the mass of CO_2 of atmospheric origin that is permanently stored" and the numerator as "the system-wide GHG emissions (CO_2e)," the DOE guidelines also recommend indicators such as "kg CO_2e per ton of CO_2 removed" and "carbon removal efficiency." When defining the functional unit, a clear distinction between gross removal and net removal is essential.
- **Clarification of system boundaries and scope**: The system boundary should be cradle-to-grave (from raw material sourcing to final storage), encompassing DAC plant construction and operation, consumables, energy supply, CO_2 compression, transport, geological storage, waste management, and decommissioning. Geographic factors related to renewable energy deployment and CO_2 transport/storage should also be considered.
- **Influence of energy sources and carbon intensity:** DAC LCA outcomes depend strongly on the carbon intensity of the electricity and thermal energy used. Renewable energy and low-carbon heat sources (heat pumps, geothermal, waste heat, etc.) can substantially improve net removal efficiency, whereas fossil energy use can markedly reduce it.
- **Co-product/by-product management and the distinction between avoided and negative emissions:** Where DAC processes yield by-products (e.g., water, oxygen, low-grade heat), co-product management should follow ISO 14044[10] hierarchy (subdivision → system expansion → allocation). “Avoided emissions” and “negative emissions” should be clearly distinguished and reported separately in LCA results.
- **Conduct of sensitivity and uncertainty analyses**: Because LCA results are strongly influenced by energy consumption, carbon intensity, consumable lifetimes, plant lifetime, and changes in efficiency during scale-up, sensitivity and uncertainty analyses should be carried out to make the influences of key parameters explicit.
- **Concurrent evaluation of other environmental impact indicators**: In addition to climate change impacts (CO_2e emissions), LCAs should simultaneously evaluate

other environmental indicators—such as land use, water consumption, consumption of metal/mineral resources, human toxicity, and ecotoxicity—and make trade-offs and secondary impacts explicit.

- **Consideration of technology learning curves and future scenarios**: LCA should account for learning-curve effects associated with large-scale deployment of DAC (reductions in cost, energy use, and material use) and scenarios for future decarbonization of the power grid.
- **Implications for policy and technology selection**: When interpreting LCA results, the influences of assumptions regarding functional units, system boundaries, co-product management, and sensitivity analyses should be fully considered. In policy decisions and technology selection, the range of interpretation arising from differing assumptions should be made explicit.

Appendix 2: Result of the past survey

For reference, the results of the research paper survey on DAC technology conducted by the Ministry of Economy, Trade and Industry in fiscal year 2023 are shown below. As a minor update, some information regarding 2025 literature has also been revised.

Article 1

Year	2011
Title	Economic and energetic analysis of capturing CO2 from ambient air
Author (main)	Kurt Zenz House et al.
Country	USA
Type of Analysis	Assessment empirical analyses
Target/Calculation/Measurement	Calculation
LCA	No
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	Not mentioned
Separation technology	Air capture (solvent, sorbent)
CO2 source	ambient air
Approach & System Boundary	Literature review and analysis Part 1: The Sherwood Plot and the Cost of Separating Dilute Streams Part 2: Minimum Work and Second-Law Efficiency Part 3: The Cost of Power to Operate Air Capture of CO2/ Part 4: Work Required to Remove Trace Gases from Mixed Gas Streams. Part 5: Design Trade-offs for Air Capture Systems
Scenarios/Samples	Not mentioned
Capacity	Not mentioned
LCA: Assumptions, Methods	Not mentioned
Unit	$/tCO2, kJ/mol CO2
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Required Energy Based on the analysis of minimum work and second-law efficiency, theoretical minimum work is 400 kJ of work per mole of CO2. But It is very likely that CO2 capture from air will require more thermodynamic work than the approximate 500 kJ/mol used for Nox removal.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Theoretical air capture cost based on Sherwood Plot (1959): Air capture cost is about $2,500/tCO2. Theoretical air capture cost based on Second-Law Efficiency: With carbon-free electricity price of 10 ¢/kWh, the cost of required CO2-free work is about $253/tCO2 for the air capture system.
TEA: Other cost-related results	Not mentioned

Article 2

Year	2014
Title	Reducing the Cost of Ca-Based Direct Air Capture of CO2
Author (main)	Frank Zeman
Country	Canada
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	No
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	Not mentioned
Separation technology	DAC (causticization of the alkaline liquid using hydrated lime (Ca(OH)2) followed by the calcination (decomposition) of the resultant calcite (CaCO3) to produce lime (CaO) and CO2)
CO2 source	ambient air
Approach & System Boundary	Approach: This work builds on the American Physical Society (APS) report (2011) to investigate the effect of modifications to the air capture system based on suggestions in the report and subsequent publications. APS report is revisited to estimate the effect of various assumptions on the energy penalties and costs associated with calcium (Ca) based air capture systems.
Scenarios / Samples	combined by purchasing electricity from a facility with CCS or building a dedicated facility at the DAC site
Capacity	1 Mt CO2/year
LCA: Assumptions, Methods	Thermal Efficiency: overall thermal efficiency (ote) of 75%. Emission factor for electricity The size of the power plant for a 1 Mt CO2/year DAC facility would be between 50 and 100MW. Here we consider electricity from coal power with CCS at a cost of $139/MWh with unit emissions of 121 kg CO2/MWh, case 10 in30 and an NGCC facility at a cost of $107/MWh with unit emissions of 43 kg/MWh, case 14 in Haslbeck et al.
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	According to the Panel on Public Affairs (POPA) of the American Physical Society (APS), the estimated cost of DAC is $610/tCO2 avoided. By reviewing the CAPEX and OPEX, the authors made modification of the cost of DAC and found $309/tCO2.
TEA: CAPEX	CAPEX: APS report and modified system Capital Costs (10^6 $) [APS / modified] - Contactor: 290 / 290 - Calciner: 120 / 112.6 - Precip. : 25 / 23/5 - ASU: 15 / 13/7 - Comp. : 30 / 28.8 - Total: 480 / 468.7
TEA: OPEX	OPEX: APS report and modified system Operating Costs ($/tCO2 avoided)[APS / modified] - Capital: 260 / 254 - O&M: 87 / 85 - Electricity : 35 / 34 - Fuel: 46 / 38 - Fugitive : 182 / 169 - Total: 610 / 580
TEA: Cost of product(s)	Optimization of the Modified Air Capture Costs Avoided

	- APS report: \$610/tCO2avoided - Modified cost: \$309/tCO2avoided = \$165/tCO2 capital + \$138/tCO2 operating + \$6/tCO2 fugitive (optimal: onsite NGCC facility with CCS combined with heat integration and the use of plastic packing in the towers)
TEA: Other cost-related results	Not mentioned

Article 3

Year	2016
Title	Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants
Author (main)	Mahdi Fasihi et al.
Country	Finland
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	No
TEA	Yes
Type of NETS	DAC, Power to liquid
Emission: Negative or Avoided	Avoided
Separation technology	DAC (approach from Climeworks)
CO2 source	Atmospheric CO2
Approach & System Boundary	Approach: Production of E-diesel by two routes: (1) Hybrid PV-Wind-PtL value chain with alkaline electrolysers and RWGS (reverse water gas shift) units (2) Hybrid PV-Wind-PtL value chain with solid oxide co-electrolyser
Scenarios / Samples	Not mentioned
Capacity	CO2 production: 5.140 million ton/yr
LCA: Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	Assumptions General - WACC (Weighted Average Cost of Capital): 7% (7%) - Exchange rate: 1.35 USD/€ (1.35USD) - Brent crude oil price: 80 USD/bbl (80USD) Hybrid PV-Wind power plant specification for annual analysis scenario - Irradiation (single-axis): 2410 kWh/(m2·a) (2410kWh/m2a) - PV performance ratio (PR): 83 % (83%) - PV yield 2000 kWh/kWp (2000kWh/kWp) Installed capacities(FLh: annual full load hours) - PV single-axis installed capacity: 5 GWp (5GWp) - Wind installed capacity: 5 GWp (5GWp) - PV single-axis FLh: 2000 h (2000h) - Wind FLh: 5200 h (5200h) - PV and Wind overlap: 5 % - Hybrid PV-Wind FLh: 6840 h
TEA: CAPEX	DAC plant specification (Climeworks) - Capex: 228 €/(tCO2·a) - Lifetime: 30 years
TEA: OPEX	DAC plant specification (Climeworks) - Opex: 4 % of capex p.a. - Electricity demand: 225 kWhel/tCO2

Article 4

Year	2017
Title	Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe—Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World
Author (main)	Mahdi Fasihi et al.
Country	Finland
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	No
TEA	Yes
Type of NETS	DAC, Synthetic fuel
Emission: Negative or Avoided	Avoided
Separation technology	DAC
CO2 source	Atmosphere
Approach & System Boundary	Approach: Production potential of PtG–LNG and PtL in the Maghreb region (North Africa) to Europe (in 2030 and 2040) System Boundary: Renewable electricity, DAC, Electrolyser , Desalination plant, Methanation plant, Liquefaction plant, Shipping / pipeline to Europe, Regeneration (gasification)
Scenarios / Samples	Assumed Value Chains: (1) Hybrid PV–Wind–PtG–LNG value chain - Renewable source: PV, Wind in Maghreb region - Production: DAC, alkaline electrolyser , desalination plant (osmosis), metanation plant - Liquefaction to LNG, LNG shipping - Shipping to North Europe, or pipeline to South Europe - Regeneration (gasification) (2) Hybrid PV–Wind–PtL value chain - Renewable source: PV, Wind (backup: combined cycle gas turbine using LFG/SNS) - Production: DAC, alkaline electrolyser, desalination plant (osmosis), FT plant - Hydrocracker - Shipping to North Europe WACC: 7% (base scenario) or 5% (de-risk scenario) CO2 emission cost: Zero or 61€/tCO2 O2 benefit: Zero or 20€/tO2
Capacity	-
LCA: Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Not mentioned

TEA: Assumptions & Methods	Assumptions: - Global crude oil price: 40–200 USD/barrel - CO2 emission cost: zero or 61 €/ton - O2 sales: zero or 20 EUR/ton - WACC (Weighted Average Cost of Capital): 5% or 7% Parameters: (1) Alkaline Electrolyser: Capex [€/kWel] 328 / 268; Opexfix [% of capex p.a.] 4; Opexvar [€/kWh 0.0012; Lifetime [years] 30; EtH2 eff. (HHV) [%] 84; Electricity-to-heat [% of inlet E] 8; (2) Methanation: Capex [€/kWSNG] 278 / 226; Opex [% of capex p.a.] 4; Lifetime [years] 30; Efficiency (HHV) [%] 77.8 (3) Hydrogen Storage: Capex [€/kWhH2] 0.015 (4) Hypothetical H2tL (RWGS, FT and Hydrocracking) Plant : Capex [k€/bpd] 60 / 54; Opex [% of capex p.a.] 3 ; Lifetime [years] 30 ; RWGS carbon conversion [%] 97.5 ; FT carbon conversion [%] 95 ; FT C5+ selectivity [%] 95 ; hydrocracking eff. [%] 98
TEA: CAPEX	CO2 Direct Air Capture Plant [2030/2040] - Capex [€/(tCO2a] 228 / 184 - Lifetime [years] 30
TEA: OPEX	CO2 Direct Air Capture Plant [2030/2040] - Opex [% of capex per.a.] 4 / 4 - Electricity demand [kWhel/tCO2] 225 / 210 - Heat demand [kWhth/tCO2] 1500 / 1350
TEA: Cost of product(s)	The direct air capturing CO2 units in the current system are mainly powered by waste heat from the PtG or PtL plants and can deliver CO2 with a cost range of 30–80 €/tonne in an optimized PtX system.
TEA: Other cost-related results	RE-SNG and RE-diesel production cost in the Maghreb region and regasified RE-SNG price in Finland (1) Minimum cost in 2030 * RE-SNG: 76€/MWhHHV (0.78€/m3) * RE-diesel: 88€/MWhHHV (0.85€/L) (2) Minimum cost in 2040 * RE-SNG: 76€/MWhHHV (0.78€/m3) * RE-diesel: 88€/MWhHHV (0.85€/L)

Article 5

Year	2017
Title	A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO2 versus MEA-Based Postcombustion Capture
Author (main)	Coen van der Giesen et al.
Country	Netherlands, USA, Italy
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	No
Type of NETS	distributed HS-DAC (compared with MEA-based PCC)
Emission: Negative or Avoided	Avoided (MEA-based PCC) HS-DAC (Negative Emission) HD-DAC+ power generation by coal fired power plant (net avoided)
Separation technology	Monoethanolamine (MEA) -Postcombustion capture Humidity Swing (HS) -DAC
CO2 source	postcombustion capture: coal-fired power plant (12% concentration) DAC: air
Approach & System Boundary	Approach: Comparison of consumed energy between: (1) MEA-based postcombustion capture (MEA-PCC) for flue gas (coal-fired power plant) (2) Humidity Swing Direct Air Capture (HS-DAC) The amount of CO2 by DAC equals to CO2 amount from power plant. The LCA covers impacts of all materials and processes in the power generation and CCS system up to providing 100 bar CO2 at injection sites. This includes mining, transporting, and combusting coal, building the power plant, transmission, and the CO2 capture and compression units, photovoltaic (PV) panels, as well as hardware decommissioning and material disposal. Only preparing the injection sites themselves is not included because the infrastructure requirements are the same for PCC and DAC and, in any case, have been shown to be of minor impact in CCS LCA studies.
Scenarios / Samples	Scenarios: - Base case: Coal-fired power plant without any mitigation - HS-DACcoal : 90% CO2-capture,Electricity from coal fired power plant - MEA-PCCPV : CO2-capture amount is same as MEA-PCCcoal, Electricity from coal fired power plant - HS-DACcoal(zeroGHG) :Same as HS-DACcoal, but CO2-capture amount is increased to achieve Net-Zero (LCA base) - HS-DACPV(zeroGHG) : Same as HS-DACcoal(zeroGHG), but with electricity from PV - MEA-PCCcoal+HS-DACPV(zeroGHG) : Combination scenario of MEA-PCCcoal and HS-DACPV - MEA-PCCcoal: capture 90% of stack CO2 emissions from combusting coal in the plant - HS-DACcoal: Coal-fired electricity generation combined with HS-DAC, set to capture an amount of CO2 such that total net lifecycle GHG emissions per kWh electricity available for end-use are the same as in the MEA-PCCcoal.
Capacity	- Plant capacity: Coal-fired power plant (500 MW) - CO2 emission: 1.49 × 10^6 ton/yr
LCA: Assumptions, Methods	Assumptions: - Coal-fired power palnt: 2 TWh with 0.744 kg-CO2/kWh - Capture efficiecny: 90% Energy requirement: MEA-PCC: (i) current/likely case 290 kWh/tCO2 captured, (ii) future/best case 211 kWh/tCO2 captured HS-DAC: 24 kWh/tCO2 for evacuation, 145 kWh/tCO2 for drying, 196 kWh/tCO2 for compressing, and 12.6 kWh/tCO2 for auxiliary. The plant's CO2 emissions without capture (base case) are 0.744 kgCO2/kWh.
Unit	kgCO2eq/kWh

LCA: CO2 NETS	- Base case: 0.85 kgCO2eq/kWh - MEA-PCC: 0.23 kgCO2eq/kWh - HS-DACcoal : 0.23 kgCO2eq/kWh - MEA-PCCPV : 0.20 kgCO2eq/kWh - HS-DACcoal(zeroGHG) :0 kgCO2eq/kWh - HS-DACPV(zeroGHG) : 0 kgCO2eq/kWh - MEA-PCCcoal+HS-DACPV(zeroGHG) : 0 kgCO2eq/kWh
LCA: Other CO2-related results	Required amount of CO2 captured - MEA-PCC: 0.83 kgCO2/kWh - HS-DACcoal : 0.93 kgCO2/kWh - MEA-PCCPV : no value shown - HS-DACcoal(zeroGHG) :1.28 kgCO2/kWh - HS-DACPV(zeroGHG) : 0.88 kgCO2/kWh - MEA-PCCcoal+HS-DACPV(zeroGHG) :no value shown Other impacts: The increased background processes such as manufacturing additional hardware and mobilizing more materials such as coal (except in the PV scenarios), sorbent, and water increase other environmental impacts per functional unit.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Assumption for OPEX [MEA-PCC]: - Electricity: 378 kWh/tonne CO2 at $0.07/kWh = $26.5/tonne CO2 - water: 15.2m3/tonne CO2 at $0.40 per m3 = $6.1/tonne CO2 - Makeup sorbent filters using Marathon A: 1.52 kg/tonne CO2 at $6/kg = $9.1/tonne CO2 - Total direct operational cost: $42 per tonne CO2
TEA: Cost of product(s)	HS-DAC cost: Consumption of electricity (20 ℃|30% case, 378 kWh/tonne CO2 at $0.07/kWh = $26.5/tonne CO2),15 water (15.2m3/tonne CO2 at $0.40 per m3 = $6.1/tonne CO2) and makeup sorbent filters using Marathon A (1.52 kg/tonne CO2 at $6/kg = $9.1/tonne CO2) would yield direct operational costs of $42 per tonne CO2.
TEA: Other cost-related results	CAPEX assumption from OPEX [HS-DAC] Benchmarking HS-DAC costs against a lower bound of $60 per tonne CO2 for MEA-PCC, this would leave $18/tonne CO2 for HS-DAC capital charge and O&M costs, or ~$43,000 capital layout for a 1 tonne CO2/day HS-DAC unit (assuming capital charge of 10% of capital layout and annual O&M costs of 5% of capital layout). A more conservative CO2 price of $100/tonne would allow ~$142,000 per unit.

Article 6

Year	2018
Title	A Process for Capturing CO2 from the Atmosphere
Author (main)	David W. Keith el al.
Country	Canada
Type of Analysis	simulation calculate
Target / Calculation / Measurement	Calculate
LCA	Yes
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	Not mentioned
Separation technology	an aqueous KOH sorbent coupled to a calcium caustic recovery loop
CO2 source	air
Approach & System Boundary	System: Carbon Engineering: The design captures 1 Mt-CO2/year in a continuous process using an aqueous KOH sorbent coupled to a calcium caustic recovery loop. Approach: We describe the design rationale, summarize performance of the major unit operations, and provide a capital cost breakdown developed with an independent consulting engineering firm.We report results from a pilot plant that provides data on performance of the major unit operations. We summarize the energy and material balance computed using an Aspen process simulation. System Boundary: Figure 2 provides a simplified energy and material balance of the complete process.
Scenarios / Samples	A: Baseline: gas fired → 15 MPa CO2 output B: Baseline with Nth plant financials C: Gas and electricity input → 15 Mpa CO2 output D: Gas and electricity input → 0.1 MPa CO2 output assuming zero cost O2
Capacity	1Mt-CO2/year DAC plant
LCA: Assumptions, Methods	Contactor Fan energy: 61 kWh/tCO2 Fluid pumping energy: 21 kWh/tCO2 Fraction of CO2 captured: 74.5% Capture rate unit inlet area: 22 tCO2/m2/year Pellet Reactor Calcium retention: 90% Fluid pumping energy: 27 kWh/tCO2 Calciner CaCO3 → CaO conversion efficiency: 98% Energy consumption: 4.05 GJ/tCO2 Slaker Power produced from slaking heat: 77 kWh/tCO2 Conversion to CaO: 85% Auxiliary Equipment Specifications ASU power usage: 238 kWh/tO2 CO2 absorber—capture frac: 90% CO2 absorber pressure drop: 1kPa
	Compressor power usage: 132 kWh/tCO2 We used a natural gas emission factor of 63.8 kg-CO2e/GJ-NG for upstream and direct combustion emissions
Unit	tCO2
LCA: CO2 NETS	Fugitive leakage from the DAC facility was combined with estimates for leakage during transport and injection and geological storage. The net result was that 0.9 tons of CO2 were permanently sequestered for each ton captured from air.
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	Methods: Total direct field costs (TDFC) =Equipment cost (EC)+Materials cost (MC)+Labor cost (LC)

TEA: CAPEX	Capacity Assumption: 0.98 Mt-CO2/year (1)Early plant - Total direct field costs (TDFC) = $697.7 - Indirect field costs (IFC) = $88.5 - Engineering = $135.2 - Other project cost = $48.2 - Contingency = $157.2 - Total project cost = $1,126.8 (2) Nth plant (improved plant) - Total direct field costs (TDFC) = $510.1 - Indirect field costs (IFC) = $68.8 - Engineering = $78.0 - Other project cost = $35.8 - Contingency = $86.8 - Total project cost = $779.5
TEA: OPEX	Energy costs: - Natural gas cost: 3.5 $/GJ - Electricity cost: 30 and 60 $/MWhr.
TEA: Cost of product(s)	Levelized costs per ton CO2 captured (LCOC) LCOC = levelized capital cost + non-fuel-O&M + energy costs = $94 - $232 /tonCO2
TEA: Other cost-related results	Summary Performance of Various Plant Configurations (CRF 7.5% / 12.5%) A: Baseline: gas fired --> 15 MPa CO2 output: 168 / 232 B: Baseline with Nth plant financials: 126 / 170 C: Gas and electricity input --> 15 MPa CO2 output: 113–124 / 152–163 D: Gas and electricity input --> 0.1 MPa CO2 output assuming zero cost O2: 94–97 / 128–130

Article 7

Year	2018
Title	Closing the carbon cycle to maximise climate change mitigation: power-to-methanol vs. power-to-direct air capture
Author (main)	H. A. Daggash et al.
Country	UK, Germeny
Type of Analysis	Assessment of mitigation potential and cost
Target / Calculation / Measurement	Calculation
LCA	Yes
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	power-to-methanol (avoided emission) power-to DAC (DACCS) (negative emission)
Separation technology	the DAC plant assumes a potassium hydroxide (KOH) process
CO2 source	atmosphere
Approach & System Boundary	Approach: The amount of curtailed renewable energy that is likely to be available in the medium term the extent to which transport-related CO2 emissions can be avoided via a power-to-fuel strategy to contrast power-to-fuel with the counterfactual argument of using the otherwise curtailed renewable energy to directly remove CO2 from the atmosphere via a direct air capture (DAC) process. System Boundary: - Hydrogen plant, methanol plant, DAC, - [power-to-fuel] Methanol car
Scenarios / Samples	Scenario: Curtailment of intermittent renewable energy sources (iRES) in UK (the level of curtailed energy is unlikely to increase beyond 2.5% until renewable power accounts for more than 50% of total installed capacity. This is unlikely to be the case in the UK before 2035.)
Capacity	Air flow to DAC: 28.2 ton/yr (to produce methanol at 1 ton/yr) 1277 GWh per year of curtailed renewable energy supports the production of approximately 140 million litres of methanol annually. On the basis of 1277 GWh y-1 electricity availability, DAC can avoid 0.7–2.1% of the UK's 2016 gasoline-derived emissions at a cost of $430–660 tCO2 avoided-1. Using this electricity for methanol production and subsequent recycling of CO2, however, can avoid 0.37% of gasoline-derived emissions at a cost of $640–870 tCO2 avoided-1.
LCA: Assumptions, Methods	Assumptions: The DAC plant assumes a potassium hydroxide (KOH) process. Only curtailed electricity is assumed to be available in this study, an electricity-driven DAC plant is assumed. Of the energy available from the fuel, only about 25% actually gets applied to moving a car (with a gasoline ICE) or running the accessories, the rest is lost to the exhaust gases, coolant, and friction. A reduction in the associated energy losses by ICEs will serve to minimise fuel consumption and improve process efficiency in the future. This conversion ratio has however been assumed for the M100 methanol car in this study. Gasoline-powered car is assumed to emit 1.3 tCO2 annually.
Unit	tCO2 avoided/MWh of curtailed power
LCA: CO2 NETS	Avoided Emissions: power-to-DAC: 0.23–0.67 tCO2 avoided/MWh of curtailed power. power-to-Fuel: 0.13 tCO2 avoided/MWh.

LCA: Other CO2-related results	In any well-designed and professionally operated electricity system, the spectre of significant quantities of curtailed renewable i. energy is unlikely to appear in the medium to long term. In order to avoid lock-in to partial decarbonisation scenarios, any fossil carbon which is extracted from the geosphere must be promptly returned to the geosphere. The reduced combustion temperatures by pure methanol engine can lead to simultaneous low soot and NOx emissions.59,60 Reduced soot and smoke emissions also result due to the higher oxygen content. This is particularly important given contemporary focus on the negative human health outcomes associated with the use of gasoline and diesel fuels. Furthermore, the low lubricity of alcohols, and corrosion susceptibility of metals in alcohols, make fuel additives necessary. Emissions of formaldehyde, acetaldehyde and any unburned methanol are also not sufficiently understood, thus present potential health risks.
TEA: Assumptions & Methods	Assumption: Electricity: $56.4/MWh The electrolysis plant: 172 ktO2 annually as a by-product (source of oxygen for the DAC plant in power-to-fuel was considered) Typical cost assumptions in the methanol sysntesis process Fossil CO2: 37–120 $/t (from a cola plant with post-combustion capture) Non-fossil CO2: 450–550 $/t (from DAC plant) Fossil H2: 1,300–2,100 $/t Electrolytic H2: 4,200 $/t
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Costs to CO2 avoided: power-to-fuel: $209/tCO2 avoided, in addition to requiring an additional $430–660/tCO2 avoided to finally close the carbon cycle by air capture. power-to-DAC: $430–660/tCO2 avoided. Typical prices of chemicals in the methanol synthesis process: Fossil CO2: 37–120 $/t Non-fossil CO2: 450–550 $/t Fossil H2: 1,300–2,100 $/t Electrolytic H2: 4,200 $/t CH3OH: 450 $/t
TEA: Other cost-related results	Profitability: For power-to-fuel to become profitable, hydrogen prices would need to be less than or equal to $1635/tH2 or methanol prices must increase to $960/tMeOH. Absent this change in H2 price or methanol value, a subsidy of approximately $283/tCO2 would be required.

Article 8

Year	2018
Title	Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents
Author (main)	Melinda M.J. de Jonge et al.
Country	Netherlands
Type of Analysis	Assessment
Target / Calculation / Measurement	Calculation
LCA	Yes
TEA	No
Type of NETS	DAC
Emission: Negative or Avoided	Negative Emission
Separation technology	DAC system based on NaOH solution
CO2 source	ambient air
Approach & System Boundary	Approach: Life cycle carbon efficiency (Ec) of a DAC system (the net amount of carbon stored per amount of carbon captured from capture to geological storage) The aim of this study was to assess the life cycle carbon efficiency of DAC systems and to identify the major contributors to the carbon balance. We included the full life cycle of DAC from capture to geological storage and included CO2 as well as other GHG emissions during construction of the necessary facilities as well as operating GHG emissions from energy and other resources needed.
Scenarios / Samples	Scenarios: Baseline / Optimistic / Pessimistic Lifetime (yr): 20, 40, 10 Mass transfer coefficient (KL, mms-1): 1.5, 2.0, 0.8 Relative humidity (RH, %): 65, 82, 38 Temperature (T, ℃): 13, 9.4, 21 Carbon footprint electrical energy source (kg CO2 eq. kWh-1): 0.50, 0.05, 1.06 Electricity (kWh tonne-1 CO2 captured): 193, 172, 278 Heat CaO cooling (MJ tonne-1 CO2 captured): -864, (-), 0 Heat flue gas cooling (MJ tonne-1 CO2 captured): -1224, (-), 0 Heat water condensation (MJ tonne-1 CO2 captured): 0, -1179 , (-) Heat calcination (MJ tonne-1 CO2 captured): 4470, (-), (-)
Capacity	Capture rate: 1 MtCO2/yr
LCA: Assumptions, Methods	Assumptions: • Construction: based on an earlier study • Energy requirements: - fans and sorbent pumps - regeneration process: based on an earlier study - compression and geological injection: based on an earlier study • Water loss: based on an earlier study • Sorbent and lime requirements: based on an earlier study • Carbon capture efficiency: (excluded GHG emissions related to the construction of the regeneration infrastructure) Ec = (CO2,cap - GHGlc) / CO2,cap x 100 Where - CO2,cap: total amount of kg CO2 stored over the lifetime of the system - GHGlc: total amount of GHG emitted over the life cycle of the system
Unit	g CO2 per kg sorbent tCO2eq emitted/tCO2 captured (Fig 2) (net CO2eq captured/CO2 captured) * 100 (carbon capture efficiency)
LCA: CO2 NETS	* Carbon capture efficiency: 62% (optimistic 93%, pessimistic 10%)
LCA: Other CO2-related results	Impacts on LCA: GHG emissions due to the electricity demand have the largest impact on the life cycle Ec.

TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 9

Year	2019
Title	Direct Air Capture of CO2: A Key Technology for Ambitious Climate Change Mitigation
Author (main)	Christian Breyer et al.
Country	Finland, Germany
Type of Analysis	review
Target/ Calculation/Measurement	(review)
LCA	Yes
TEA	No
Type of NETS	DAC, DACCS, DACCU
Emission: Negative or Avoided	Not specified
Separation technology	DAC
CO2 source	atmosphere
Approach & System Boundary	review
Scenarios / Samples	Not mentioned
Capacity	-
LCA: Assumptions, Methods	Not mentioned
Unit	GtCO2/a
LCA: CO2 NETS	Classification of DAC Applications into Utilization (DACCU) and Long-Term Storage (DACCS) and Comparison to the Bioenergy Alternative and Fossil Fuel Reference Fossil fuels fossil CCU (limited to point sources) <-- conflict potential to sustainability limits fossil CCS (limited to point sources) <-- conflict potential to sustainability limits Bioenergy BECCU (residues, wastes by-products) <-- compatibility to sustainability limits BECCS (energy crops) <-- conflict potential to sustainability limits Solar and Wind DACCU (electricity, optional waste heat) <-- compatibility to sustainability limits DACCS (electricity, optional waste heat) <-- compatibility to sustainability limits
LCA: Other CO2-related results	The relatively young research field of DAC technology still exhibits several research questions, which have not yet been well addressed. Sorbents with high CO2 capacity, easily regenerable, favorable kinetics, and long lifetime need more development. In addition, the DAC performance under different weather conditions and integration of DAC to systems with abundant waste heat needs to be demonstrated. Lifecycle assessment studies for DAC17 are still very limited and require more attention. A detailed global inventory of all CO2 point sources, which would still be available under strict sustainability criteria, such as cement mills, pulp and paper plants, and waste incinerators, is required. Since such sources can be used first for CCU processes. The remaining CO2 raw material demand for hydrocarbon-based fuels and chemicals can be covered by DAC.The learning rate of DAC is not yet understood well but has a substantial impact on DAC cost projections
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Global CO2 DAC cost map for 2050:
TEA: Other cost-related results	*If in addition a scalable negative emission technology can deliver CO2 sequestration at costs of less than 100 USD/tCO2, it becomes feasible to imagine trajectories that reduce temperatures to 1 C until 2100–2150.

Article 10

Year	2019
Title	An inter-model assessment of the role of direct air capture in deep mitigation pathways
Author (main)	Giulia Realmonte et al.
Country	Italy, UK, Ireland
Type of Analysis	Integrated Assessment Modeling (IAM) study
Target/Calculation/Measurement	Calculation, Target
LCA	Yes
TEA	No
Type of NETS	DACCS, BECCS, afforestation
Emission: Negative or Avoided	Negative emission
Separation technology	hydroxide sorbents (DAC1) / MEA (DAC2)
CO2 source	atmosphere
Approach & System Boundary	Approach: Inter-model comparison on the role of DACCS in 1.5 and 2 C scenarios, under a variety of techno-economic assumptions
Scenarios / Samples	Central case scenarios: - NoNET: No BECCS and no DACCS, only afforestation allowed (+traditional CCS) - NoDAC: No DACCS available, only BECCS and afforestation as NETs (+traditional CCS) - DAC: Full NET portfolio: DACCS, BECCS and afforestation (+traditional CCS) Carbon budgets imposed (2016-2100), 66% probability: - 2 C scenario: 810 GtCO2 - 0.5 C scenario: 220 GtCO2 DACCS models, based on Integrated Assessment Modeling (IAM) (1) bottom-up technology rich model (TIAM-Grantham) (2) hybrid, economy-climate model (WITCH) 1.5 C (not 0.5 C) scenario: 220 GtCO2
Capacity	Rrequired DACCS scale-up rate: 1.5 GtCO2/yr (average) Max cap: 30 GtCO2/yr for DAC scenario, 3GtCO2/year for Gt scenarios
LCA: Assumptions, Methods	DAC system DAC 1: water solutions containing hydroxide sorbents - Electricity[GJ/tCO2]: high 1.8, low 1.3 - Heat [GJ/tCO2]: high 8.1, low 5.3 - Cost [$/tCO2]: high 300, low 180, floor 100 * DAC 2: amine materials bonded to a porous solid support - Electricity[GJ/tCO2]: high 1.1, low 0.6 - Heat [GJ/tCO2]: high 7.2, low 4.4 - Cost [$/tCO2]: high 350, low 200, floor 50 DAC1: Additional CCS unit for burning natural gas with a capture efficiency equal to 95% Land requirement: 1.5 m2/tCO2/year (DAC1), 0.05-0.1 m2/tCO2/year (DAC2) Water consumption: about 5 to 13 tonne of water per each tonne of CO2 captured (DAC1)
Unit	Scale-up rate (GtCO2/yr) Cumulative sequestration (Gt)
LCA: CO2 NETS	Cumulative sequestration of negative emissions technologies throughout the century in central case scenarios
LCA: Other CO2-related results	DACCS scale-up rates of 1.5 GtCO2/yr would require considerable sorbent production and up to 300 EJ/yr of energy input by 2100.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 11

Year	2019
Title	Techno-economic assessment of CO2 direct air capture plants
Author (main)	Mahdi Fasihi et al.
Country	Finland
Type of Analysis	TEA
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	Yes
Type of NETS	DAC, DACCS
Emission: Negative or Avoided	Negative Emission or avoided by CCU
Separation technology	HT aqueous solution-based DAC LT solid sorbent-based DAC
CO2 source	atmosphere
Approach & System Boundary	Approach: - Literature review and techno-economic analyses of state-of-the-art DAC technologies - DAC technologies are categorised as high temperature aqueous solutions (HT DAC) and low temperature solid sorbent (LT DAC) systems, from an energy system perspective.
Scenarios / Samples	System: Moroccan hybrid PV-Wind-battery plants and heat pumps Scenarios: The conservative scenario assumes only 50% realisation of the cumulative DAC capacity demand due to delayed execution of the Paris Agreement and a DAC learning rate of 10%. The base case scenario assumes an effective execution of the Paris Agreement without delay, leading to net zero GHG emissions from the energy system and already started CO2 removal. The DAC learning rate is assumed to be 15%.
Capacity	2020: 3.0 MtCO2/a 2030: 473 MtCO2/a 2040: 4,791 MtCO2/a 2050: 15,356 MtCO2/a
LCA: Assumptions, Methods	Assumptions: - O2 is available for free, thus power demand and costs of CO2 compressor and air separation unit have been avoided. - CO2 purity of more than 99% has been assumed for the final model as an average of CO2 purity from Climeworks, Global Thermostat and Antecy. - the targets of the Paris Agreement shall be achieved by the mid of this century. HT DAC: 1535 kWhel/tCO2 (in 2020) from CSP. 1316 kWhel/tCO2 (in 2050 conservative scenario) LT DAC: 250 kWheltCO2, 1750 kWhth/tCO2 (in 2020) from heat pump/waste heat. 182 kWheltCO2, 1102 kWhth/tCO2 (in 2050 conservative scenario)
Unit	MtCO2/a
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Global annual CO2 DAC (or equivalent) capacity demand by sector Sector: - Power (power-to-gas, waste-to-energy, and sewage plant) - Transport (road, rail, marine, and aviation) - Industry (chemical industry, pulp and paper, cement mills, and others) DAC capacities of 3 MtCO2/a (2020), 470 MtCO2/a (2030), 4798 MtCO2/a (2040) and 15,402 MtCO2/a (2050) are needed.
TEA: Assumptions & Methods	Calculations: - Levelised cost of electricity (LCOE) LCOE = { (Capex x crf + Opexfix) / FLh } + Opexvar + (fuel / η)

	- Levelised cost of heat (LCOH) $LCOH = \{ (Capex \times crf + Opex_{fix}) / FLh \} + Opex_{var} + (fuel / \eta) + (LCOE / COP)$ - Levelised cost of CO2 DAC (LCOD) $LCOD = \{ (Capex_{DAC} \times crf + Opex_{fix}) / Output_{CO2} \} + Opex_{var} + DAC_{el.input} \times LCOE + DAC_{th.input} \times LCOH$ $crf = \{ WACC \times (1 + WACC)^N \} / \{ (1 + WACC)^N - 1 \}$ Whereas - capex: capital expenditures - crf: annuity factor - opex: annual operational expenditures - fix: fixed expenditures - var: variable expenditures - $Output_{CO2}$: annual CO2 production of DAC plant - FLh: full load hours per year - $DAC_{el.input}$: electricity demand of DAC plant per tCO2 produced - $DAC_{heat.input}$: heat demand of DAC plant per tCO2 produced - fuel: fuel costs - η: efficiency - COP: coefficient of performance of heat pumps - WACC: weighted average cost of capital (7%) - N: lifetime
TEA: CAPEX	<u>Long-term specifications of DAC and generic costs (conservative scenario)</u> CAPEX [€/tCO2$a] <2020 / 2030 / 2040 / 2050> - LT DAC: 730 / 338 / 237 / 199 - HT DAC: 815 / 378 / 265 / 222
TEA: OPEX	<u>Long-term specifications of DAC and generic costs (conservative scenario)</u> OPEX [% of capex p.a.] <2020 / 2030 / 2040 / 2050> - LT DAC: 4% / 4% / 4% / 4% - HT DAC: 3.7% / 3.7% / 3.7% / 3.7%
TEA: Cost of product(s)	<u>CO2 capture costs</u> - LT DAC (hybrid PV-Wind-battery systems in Morocco) [€/tCO2] <2020 / 2030 / 2040 / 2050> - Without utilisation of free waste heat: 222 /105 /69 / 54 - With utilisation of free waste heat: 133 /60 /40 /32 Worldwide: In a conservative scenario with 10% learning rate of capex and the realisation of half the required DAC capacities at each time step, the capex of HT/LT DAC systems are calculated to be 815/730, 378/338, 265/237 and 222/199 €/tCO2$a in 2020, 2030, 2040 and 2050, respectively. - a 5/10% electricity demand reduction for HT/LT DAC and 14.3% low-grade heat demand reduction is foreseen at each 10-year time step. - Morocco: despite higher electricity costs, DAC systems with higher FLh would have lower LCOD. In the conservative scenario, The LCOD of HT/LT DAC systems with 8000 FLh are calculated to be 268/222, 133/105, 91/69 and 71/54 €/tCO2 in 2020, 2030, 2040 and 2050, respectively. * Morocco: base case scenario, the costs would be reduced to 268/222, 111/84, 72/53 and 54/38 €/tCO2, respectively.
TEA: Other cost-related results	Discussion: - Access to free waste heat could further decrease the LCOD of LT DAC by 40-57%, depending on the year and applied scenario. At such costs, DAC is competitive to PSCC with less restrictions on capacity and location.

Article 12

Year	2019
Title	The mutual dependence of negative emission technologies and energy systems
Author (main)	Felix Creutzig et al.
Country	Germany, Finland, UK, USA.
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	Yes
Type of NETS	DACCS BECCS
Emission: Negative or Avoided	Negative Emission
Separation technology	DACCS (liquied sorbent powered by electricity with average representative carbon intensity and gas plus CCS for heating, solid sorbents powered by PV and battery storage)
CO2 source	Atmosphere
Approach & System Boundary	Approach: Comparison between DACCS and BECCS (1) what does large-scale NETs deployment imply for energy production and consumption? (2) How much primary energy is required to remove one ton of carbon? (3) How much net carbon is avoided per unit of carbon sequestered? (4) How could costs of NETs change in a temporally evolving energy system? (5) what are the implications of NETs for power systems? System Boundary: Energy system and land use
Scenarios / Samples	Literature and Models: - Integrated assessment models - Bottom-up modelling - National Academy of Science - Industry sources (Climeworks, Global thermostat, Antecy) Scenarios: - BECCS - DACCS with solid sorbents powered by PV and battery storage - DACCS with liquid sorbent powered by electricity with average representative carbon intensity and gas plus CCS for heating DAC Scenarios: A) linear decarbonization of electricity and heat until 2100, B) linear decarbonization of electricity and heat until 2050, followed by zero emissions until 2100; and C) the same decarbonization until 2050 as in the first case, but further decarbonization of the electricity system, into negative territory (relying on BECCS), between 2050 and 2100
Capacity	CO2 capture: gigaton scale 1 GtCO2 per year in 2050
LCA: Assumptions, Methods	For DACCS: assumptions for electricity and heat (different rates of decarbonization): A) linear decarbonization of electricity and heat until 2100 B) linear decarbonization of electricity and heat until 2050, followed by zero emissions until 2100 C) the same decarbonization until 2050 as in the first case, but further decarbonization of the electricity system, into negative territory (relying on BECCS), between 2050 and 2100. DACCS system have less net CO2 emissions associated with their provisioning systems displaying a sequestration efficiency of 75–100%, compared to BECCS displaying a sequestration efficiency of 50–90% with lower values possible.

Unit	sequestration efficiency (%)
LCA: CO2 NETS	75-100%
LCA:OtherCO2-related results	The role of CO2-intensity in the energy required to power direct air capture A) Assumptions on the CO2 intensity of electricity in the scenarios B) assumptions on the CO2 intensity of heat in the scenarios C) net CO2 emissions from electricity for DACCS D) net CO2 emissions from heat for DACCS E) net annual DAC-based CO2 sequestration per year F) cumulative CO2 sequestration until 2100
TEA:Assumptions& Methods	Energy Outputs /Inputs for BECCS and DACCS (different bodies of literature and models) - Integrated assessment models (IAM) - Bottom-up modelling - National Academy of Science - Industry sources (for DAC: Climeworks, Global thermostat, Antecy)
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	DACCS: Range from $100–300 per tCO2 in 2050 (literature). BECCS: Estimated costs of $100–200 per tCO2 sequestered (literature). Carbon dioxide removal costs of DACCS are considerably higher than BECCS, but if DACCS modularity and granularity helps to foster technological learning to <100$ per tCO2, DACCS may remove CO2 at gigaton scale.
TEA: Other cost-related results	DACCS also requires two magnitudes less land than BECCS.

Article 13

Year	2019
Title	Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling
Author (main)	Christian Breyer et al.
Country	Finland
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	No
TEA	Yes
Type of NETS	DAC, DACCS
Emission: Negative or Avoided	Negative emission
Separation technology	solid-sorbent DAC
CO2 source	air
Approach & System Boundary	Approach: The LUT Energy System model of LUT University is used to analyse RE-based DAC systems in the Maghreb region. The LUT model combines full hourly resolution and coverage of the world structured into 145 regions (Breyer et al. 2017a, 2018; Ram et al. 2017a), whereof the Maghreb region is highlighted in this research. Boundary: The model includes four technological categories: electricity generation, energy storage, energy sector bridging and electrical power transmission in Maghreb region.
Scenarios / Samples	Modeling: The LUT Energy System model, developed by LUT University Power sector key specification for 2040 and 2050 in Table 1. DAC and heat sector key sepcifications for 2040 and 2050 in Table 2.
Capacity	1.04 GtCO2/a (capture capacity in 2050)
LCA:Assumptions, Methods	DAC electricity demand: 203 kWhel/tCO2 (in 2040), 182 kWhel/tCO2 (in 2050) DAC heat demand: 1286 kWhth (in 2040), 1102 kWhth (in 2050)
Unit	Not mentioned
LCA: CO2 NETS	GtCO2/yr
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	Power sector key specifications: 2040 / 2050 (1)PV fixed tilted - Capex [€/kWp] 300 / 246 - Opexfix [€/kWp] 8.8 / 7.4 - Lifetime [Years] 40 / 40 (2)PV single-axis tracking - Capex [€/kWp] 330 / 271 - Opexfix [€/kWp] 10 / 8 - Lifetime [Years] 40 / 40 (3)Wind energy (onshore) - Capex [€/kWp] 940 / 900 - Opexfix [€/kWp] 18.8 / 18 - Lifetime [Years] 25 / 25
TEA: CAPEX	DAC and heat sector: 2040 / 2050 (1) CO2 direct air capture plant Capex [€/(tCO2·a)] 234 / 196 Lifetime [Years] 30 / 30 (2) Electrical compression heat pump Capex [€/kWth 554 / 530 Lifetime [Years] 25 / 25 (3) Thermal heat storage

	Capex [€/kWhth] 20 / 20 Lifetime [Years] 30 / 30
TEA: Cost of product(s)	LCOD The annualised cost for the total DAC system is 55.3 b€, leading to LCOD of 55.3 €/tCO2 in 2050. Cost breakdown of the annualised cost of the DAC system PV plants (16.1%) wind plants (0.5%) battery units (15.3%) heat pump (16.3%) thermal energy storage (7.2%) DAC units (44.6%)
TEA: Other cost-related results	DAC system in Maghreb region in 2050: Solar PV power plants of 329.6 GWp (composed of 187.4 GWp single-axis tracking and 139.5 GWp fixed tilted systems), generating 703 TWh of electricity annually at 12.8 €/MWh LCOE primary. The FLh are 2389 (single-axis tracking) and 1830 (fixed tilted). Wind power plants of 2.7 GW, generating 9.9 TWh of electricity annually at 26 €/MWh LCOE primary. The FLh are 3660. Battery units of 156.3 GW power capacity and 937.6 GWhcap energy storage capacity. Heat pump units of 148.3 GWth capacity. The full load hours are 8297. Thermal energy storage of 1779.5 GWhth energy storage capacity.

Article 14

Year	2020
Title	Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process
Author (main)	Ali Kiani et al.
Country	Australia
Type of Analysis	TEA
Target/Calculation/Measurement	Calculation(Simulation)
LCA	No
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	Avoided Emission (synthetic methane production)
Separation technology	-
CO2 source	ambient air
Approach & System Boundary	Approach: The process of carbon dioxide (CO2) capture directly from ambient air in a conventional monoethanolamine (MEA) absorption process was simulated and optimized using a rate-based model in Aspen Plus. System Boundary: Reactor only
Scenarios / Samples	Capture rate: * Capture rate: 90% * Reboiler duty: 21.9 GJ/tCO2 Here it is assumed that a constant amount of CO2 was produced from ambient air using the MEA-based absorption process as the capture rate of the process varied from 20 to 90%. considering a capture rate of around 50% may be more feasible in terms of cost effectiveness of the air capture process a benchmark condition was selected for the capture of CO2 from air using the MEA absorption process. This point was based on a capture efficiency of 50%, a lean loading and a rich loading of 0.2 and 0.35, respectively, and a reboiler temperature of 123◦C. The rich split configuration was used in this case study due to its superior energy performance. A detailed analysis was conducted for this base case scenario, which included determination of thermal and electrical energy requirements in this system (see Table 3)
Capacity	148.25 Nm3/h of CO2 from the air production of 148.25 Nm3/h of CO2 from the air (0.291 tCO2/h at standard conditions)
LCA: Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	Model Rate-based model in Aspen Plus Conditions for the MEA-based CO2 capture process simulation * Generic conditions - CO2 concentration in inlet air, ppm: 400 - Inlet air temperature,◦C: 25 - CO2 capture rate, ton/h: 0.291

	- MEA concentration, wt%: 30 - L/G for absorber with circulation, ton/ton: 2.54 - Packing materials in absorber and desorber: Mellapak 250X - Flooding capacity of absorber/desorber (%): 70/65 - Desorber pressure (bar): 2 - Temperature approach of cross heat exchanger, K: 10 * Variable conditions - Capture rate, %: 20, 35, 50, 70, 90 - Rich loading, mol/mol: 0.27, 0.30, 0.33, 0.36 - Lean loading, mol/mol: 0.15, 0.20, 0.25 - Air relative humidity, %: 30, 50, 70, 90
TEA: CAPEX	Economic performance of MEA-based air capture --> improved amine-based air capture * Major equipment and cost element Cost, Million US$ (2016 US$) - Washing column: 4.38 - Absorber: 4.22 --> 0.70 - Desorber: 0.13 --> 0.13 - Blowers and fans 1.66 --> 1.66 - Heat exchangers: 0.39 --> 0.39 - Pumps: 0.30 --> 0.23 - Tanks: 0.40 --> 0.40 - Other equipment: 0.22 --> 0.07 - Total direct costs: 11.70 --> 3.59 - Total indirect costs: 2.27 --> 0.70 - Engineering: 1.40 --> 0.43 - Contractor fees: 0.42 --> 0.13 - Contingencies: 3.49 --> 1.07 - Total plant costs: 19.27 --> 5.91 - Spare parts: 0.096 --> 0.03 - Total investment costs: 19.37 --> 5.94
TEA: OPEX	Economic performance of MEA-based air capture --> improved amine-based air capture * Operating expenses, Million US$ (2016 US$) - Annual O&M costs: 0.757 --> 0.233 - Annual heat costs: 0.213 --> 0.213 - Annual electricity costs: 0.286 --> 0.241
TEA: Cost of product(s)	Economic performance of MEA-based air capture --> improved amine-based air capture * CO2-capture cost ($/ton CO2) - Capital: 317 --> 1,033 - O&M: 122 --> 396 - Heat: 111 --> 111 - Electricity: 126 --> 150 - CO2 capture costs: 676 --> 1,691 * Cost range: $273 - $1,227/tCO2 - Electricity: $20–$200/MWh - Heat price: $2–$20/GJ - Plant life: 15–25 years - Capital expenditure: ±30%
TEA: Other cost-related results	Not mentioned

Article 15

Year	2020
Title	Role of Carbon Capture, Storage, and Utilization to Enable a Net-Zero-CO2-Emissions Aviation Sector
Author (main)	Viola Becattini et al.
Country	Switzerland
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	Negative emission (DAC-CCS route) and avoided emissions (DAC-CCU route)
Separation technology	amine-functionalized adsorbents (based on Gabrielli et al. 2020, Sutter et al. 2019).
CO2 source	Atmosphere
Approach & System Boundary	Approach: * A quantitative assessment of these scenarios and of a business-as-usual (BAU) scenario, where aviation emissions are subjected to a carbon tax, is performed based on jet fuel cost and carbon price projections until 2050.
Scenarios / Samples	Scenarios: (i) CCS (corresponding emissions are offset by capturing CO2) - Direct air capture (DAC-CCS route) - Point-source capture (PSC-CCS route) (ii) CCU (fuel is produced by using CO2 as feedstock) - Direct air capture (DAC-CCU route) - Point-source capture (PSC-CCU route)
Capacity	Production of 1 tonne of Jet fuel Learning for DAC starts at its current total installed capacity of 3 MtCO2/y,67 which increases linearly up to 5 GtCO2/y in 2050.
LCA:Assumptions, Methods	Assumptions: - The four scenarios achieve net-zero CO2 emissions through CCS or CCU technologies, under the assumption that the processes are powered by carbon-free electricity, e.g., coming from carbon-free solar or wind. - For simplicity, in the CCU-based scenarios, we assume that synthetic fuels can fully replace fossil kerosene as drop-in fuels although currently only blending up to 50% vol. is allowed. - The use of 1 tJF emits ca. 3.10 tCO2, based on a simple carbon balance and assuming an average chemical composition of the fuel corresponding to the chemical formula C11H24. - The DAC unit is modeled as in a recent paper, and it consumes 0.25 - 1.75 MWht/ton-CO2. it consumes 0.25 MWhe and 1.75 MWht to capture one tonne of CO2
Unit	GtCO2/y
LCA: CO2 NETS	Amount [q0 --> q2050] - DAC (GtCO2/y): 0.003 --> 5 - H2 production (MtH2/y): 7 --> 158 - CO2 conversion (MtCO/y): 0.002 --> 2.5 - PSC (GW): 0.04 --> 1.2
LCA: Other CO2-related results	Discussion: When considering increasing levels of the carbon intensity of electricity production, the CO2 emissions of the CCU routes grow about 20 times faster than those of the CCS routes. Besides they are above BAU levels for a carbon intensity of electricity above about 0.07 tCO2/ MWhe. Furthermore, the smaller electricity consumption and the simpler jet fuel

	production processes of the CCS routes lead to lower jet fuel costs and to a smaller impact of the uncertainty associated with the future evolution of low-TRL technologies. In fact, the CCS-PSC route is cost competitive with BAU already today and technology ready for wide deployment. The transition to a net-zero-CO2-emissions aviation industry based on CCS can be driven by carbon prices in the order of only 70-100 €/tCO2, whereas the impact of electricity prices is limited (negligible in the case of PSC). In contrast, the transition to a CCU industry requires much higher carbon prices and/or a large increase in the availability of low cost (possibly unrealistically low) carbon-free electricity.
TEA: Assumptions & Methods	Assumptions: Jet fuel emissions: subjected to a carbon tax Electrolyser: 70% efficiency, 15 years lifetime, and 2600 full load hours of operation CO2 conversion in the electrolyer: 45% efficiency (with equal lifetime and full load hours as for H2 production) Share of products of the FT synthesis: 55% (remaining share is assumed to be diesel) Average composition of FT products: C11H24 CO2 feedstock by the aviation: Only the biogenic share of the total waste-to-energy emissions CO2 transport cost: fixed cost (with evaluation via sensitivity analysis) Electricity: renewable sources Heat: heat pumps (with coefficient of performance, COP, equal to 4) Levelized cost of electricity (LCOE): constant over the years CO2 feedstock by the aviation: Only the biogenic share of the total waste-to-energy emissions : PSC-CCU
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Cost [C0 --> C2050] - DAC [€/tCO2]: 536--> 179 - H2 production [€/tH2]: 915 --> 531 - CO2 conversion [€/tCO]: 108 --> 37 - PSC [€/tCO2]: 60 --> 33 Discussion: - Findings show that CCS-based scenarios consistently lead to lower jet fuel costs than CCU-based scenarios across the considered time scenarios and sensitivity analyses. This is mainly due to the fact that CCU-based routes result in an energy consumption more than 20 times higher than CCS-based routes, which also implies higher CO2 emissions when considering the carbon intensity of current electricity grids. - Overall, the PSC-CCS route represents the most cost-effective solution for decarbonizing the aviation industry, and it is cost competitive with BAU already today.
TEA: Other cost-related results	The transition to a net-zero-CO2-emissions aviation industry based on CCS can be driven by carbon prices in the order of only 70-100 €/tCO2, whereas the impact of electricity prices is limited (negligible in the case of PSC). In contrast, the transition to a CCU industry requires much higher carbon prices and/or a large increase in the availability of low cost (possibly unrealistically low) carbon-free electricity.

Article 16

Year	2020
Title	A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks
Author (main)	Muhammad Munir Sadiq et al.
Country	Australia
Type of Analysis	Experiment
Target/Calculation/Measurement	Measurement
LCA	Yes
TEA	Yes
Type of NETS	DAC
Emission: Negative or Avoided	Negative emission
Separation technology	MOF
CO2 source	air
Approach & System Boundary	Approach:* Developed DAC demonstrator, which contains three modules "AirthenaTM DAC demonstrator" (dimensions 1.8 × 1.4 × 1.56 m, capturing 140 gCO2/day)* MOF polymer nanocomposite: 60 kg/m3 x 10 kg* Temperature-Vacuum Swing Adsorption * Air flow rate: 50 m3/h
Scenarios / Samples	Evacuation Step (15 min) → 6min Desorption Step (10 min) → 5min Collection Step (5 min) →2min
Capacity	Feed flow rate: 50 m3/h feed at a flowrate of 50 m3/h per module 140 g/day of CO2 with a DAC demonstrator (having three modules)
LCA:Assumptions, Methods	Calculation: Eairflow = { 1 / (ηfan x Noutput } x Nflowrate x Δp x tads Where - Nflowrate: Air flow 50 m3/h - Δp: Back pressure 20 Pa - ηfan: Fan efficiency 0.8 - Eairflow: Associated energy cost 0.17 kWh/kg - tads: adsorption time 60 min - Noutput: amount of CO2 output of the per cycle Evacuum = Pambient x V x (1 / ηpump) x { pstart / pambient - pend / pambient + In (pend / pstart) } Where - Evacuum: energy consumption 0.33 kWh/kg (during an evacuation step), 0.18 kWh/kg (desorption step) - V: free volume of the canister measured at 7 L - ηpump : efficiency of the vacuum pump assumed to be 0.7 - pambient : pressure of the outside atmosphere - pstart:pressures of the canister before vacuum - pend: pressures of the canister after vacuum
Unit	kWh/kg-CO2
LCA: CO2 NETS	Minimal Energy Consumption: CO2 output at 70–80% purity over 2680 cycles and required a minimal regeneration energy of 1.6 kWh/kg-CO2 The total system energy consumption of 2.28 kWh/kgCO2 is estimated by calculating the fan and vacuum energy consumption based on measured operational performance, summarized in Table 2.
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	CAPEX: no information OPEX: only electricity (for Levelized costs of electricity for plants)
TEA: CAPEX	Not mentioned
TEA: OPEX	Levelized costs of electricity for plants in 2022 [$/MWh] * Solar photovoltaics (PV): 49.9 US$/MWh

	* Solar thermal: 126.6 US$/MWh * Hydroelectric: 61.7 US$/MWh Natural gas with CCS: 74.9 US$/MWh
TEA: Cost of product(s)	Airthena[TM] DAC technology CO2 Cost [$/ton-CO2] * Solar photovoltaics (PV): 102 * Solar thermal: 258 * Hydroelectric: 126 * Natural gas with CCS: 152 Waste heat: 45
TEA: Other cost-related results	Not mentioned

Article 17

Year	2020
Title	A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production
Author (main)	Caroline M. Liu et al.
Country	Canada
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	No
Type of NETS	DAC + E-fuel production
Emission: Negative or Avoided	Emission
Separation technology	ambient air is brought into contact with a KOH solution in the air contactor.
CO2 source	Atmosphere
Approach & System Boundary	Approach: E-fuel synthesis using DAC - DAC data: Carbon Engineering Ltd.(Canada) - FT synthesis data: literature System Boundary: Cradle (raw materials supply, incl. natural gas for the calciner, cobalt for the catalyst, KOH for the air contactor) to end use (fuel combustion)
Scenarios / Samples	Scenarios for DAC: (1) Oxy-fired calciner for DAC: - NG and O2 from electrolyzer is used for DAC (2) Electric calciner for DAC: - Electric calcinater is used for DAC The baseline scenario assumes capacity for this process (rWGS reaction and FTS process, synthetic fuel produced is assmued to be equivalent to diesel) is 1.1 MtCO2 captured from air per year, which is converted (along with CO2 captured from natural gas combustion) into 20 PJ of synthetic diesel (9800 bpd), showin in Table 1. We, thus, evaluate a variant of the baseline scenario, in which the calciner is heated electrically rather than by combusting natural gas. The difference in carbon flows between the oxy-fired (baseline) and electric calciner scenarios are shown in Fig. 2.
Capacity	full-scale plant, capturing approx. 1.1 MtCO2/yr
LCA:Assumptions, Methods	Assumptions: * Electricity carbon intensity: 13 gCO2e/kWh * H2 production method: Alkaline electrolysis (57 kWh/kgH2) * Synthetic fuel heating value: 43 MJ/kg (LHV) * End use fuel combustion emissions, 75 gCO2e/MJ (LHV) * H2 to CO produced ratio (rWGS): 1:1 * H2 to CO ratio (FT): 2:1 (molar ratio)
Unit	gCO2 captured
LCA: CO2 NETS	Llife Cycle Net Emissions of DAC: (1) Oxy-fired calciner for DAC: 0.51 gCO2e/gCO2-captured(2) Electric calciner for DAC: 0.16 gCO2e/gCO2-capturedP.3135 F 0.51 gCO2e emitted per gCO2 captured from air using an oxy-fired calciner (shown on the left) and 0.16 gCO2e emitted per gCO2 captured from air for the electric calciner alternative (shown on the right)
LCA: Other CO2-related results	Discussion: Electricity with less than 139 gCO2e/kWh is required to provide a climate benefit over conventional diesel fuel.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 18

Year	2020
Title	Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States
Author (main)	Noah McQueen et al.
Country	USA
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation Measurement
LCA	No
TEA	Yes
Type of NETS	DAC + Geological Storage / CCU
Emission: Negative or Avoided	Negative Emission
Separation technology	Solid sorbent DAC (The solid sorbent system analyzed here is based on a 5-step temperature vacuum swing adsorption process)
CO2 source	Atmosphere
Approach & System Boundary	System Boundary cradle-to-gate lifecycle model Although emissions associated with the DAC process, compression, and transportation are included, the downstream emissions from either the subsequent utilization of CO2 or the CO2 storage process are not included in the analysis. For the base case, the emissions associated with upstream natural gas leakage are also neglected.
Scenarios / Samples	Scenarios for 80% sorbent DAC thermal requirement: Base case: steam from natural gas without point-source capture Geothermal: heat extraction from the exit brine of existing geothermal power plants Nuclear: a 5% slipstream of steam from a nuclear power plant steam generator 80% sorbent… は low-cost, low-carbon heat satisfies the 80% sorbent DAC thermal requirement
Capacity	opportunity to scale to 19 MtCO2/yr
LCA: Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	DAC emissions footprint: Base case: 0.65 tCO2-emitted/tCO2-captured Geothermal and nuclear: 0.29 tCO2-emitted/tCO2-captured
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	CAPEX (100 ktCO2/year): Base case: 134 $/tCO2/yr Geothermai: 142 $/tCO2/yr Nuclear: 136 $/tCO2/yr annualized CAPEX の値
TEA: OPEX	OPEX (100 ktCO2/year): Base case: 89 $/tCO2/yr Geothermai: 80 $/tCO2/yr Nuclear: 96 $/tCO2/yr
TEA: Cost of product(s)	Total cost of capture (capital and operating): (1) Base case: $223/tCO2-captured (2) Geothermai: $205/tCO2-captured (3) Nuclear: $233/tCO2-captured Total cost of capture and storage: (2) Geothermal: $237/tCO2 net delivered Nuclear: $284/tCO2 net delivered
TEA: Other cost-related results	CCU: 70 MtCO2/yr is produced either naturally (55 MtCO2/yr) or anthropogenically (14 MtCO2/yr) to meet U.S. utilization needs. * Enhanced oil recovery (EOR): 60 MtCO2/yr

	* Chemical: 4.3 MtCO2/yr * Methanol: 2.5 MtCO2/yr * Physical use: 3 MtCO2/yr US 2018 Bipartisan Budget Act provides a tax credit of $15.29/tCO2 for EOR and utilization in 2018, increases linearly to $35t/CO2 in 2026, and rises with inflation thereafter.

Article 19

Year	2021
Title	Enhanced Activity of Integrated CO2 Capture and Reduction to CH4 under Pressurized Conditions toward Atmospheric CO2 Utilization
Author (main)	Fumihiko Kosaka et al.
Country	Japan
Type of Analysis	Experiment
Target/Calculation/Measurement	Measurement
LCA	No
TEA	No
Type of NETS	DAC Methanation
Emission: Negative or Avoided	Avoided emission
Separation technology	No separation, but CO2 capture and reduction (CCR)
CO2 source	dilute CO2 (flue gas or air)
Approach & System Boundary	Approach:Ni-based dual-functional catalysts and studied the effects of operating conditions on direct CO2 capture and reduction to CH4 using a fixed-bed reactor. Boundary:Reactor (integrated process) only.The integrated process consisted of the following steps: (i) CO2 capture for 10 s to 100 min(ii) 5 min N2 purging to remove unreacted CO2(iii) reduction of the chemically captured CO2 with H2 for 5 min
Scenarios / Samples	Experiment with 5% CO2, 13% CO2, 100 ppm CO2, and 400 ppm CO2
Capacity	500 Nml/min
LCA:Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Evaluation of Catalysts: Ni/Na-γ-Al2O3 showed the highest activity for integrated CO2 capture (5 vol % CO2 absorption) and conversion into CH4, achieving high CO2 conversion (>96%) and CH4 selectivity (>93%). It was found that the CO2 capture efficiency was particularly high when an appropriate CO2 supply period was employed.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 20

Year	2021
Title	Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption
Author (main)	Sarah Deutz and André Bardow
Country	Germany, Switerland
Type of Analysis	LCA
Target/Calculation/Measurement	Calculation Analysis of Climeworks plant
LCA	Yes
TEA	No
Type of NETS	DAC
Emission: Negative or Avoided	Negative Emission (DAC to perform CDR) and avoided emissions (the use of CO_2 from DAC)
Separation technology	six adsorbents Amine on silica Amine on alumina Amine on cellulose Carbonate on silica Carbonate on silica Anionic resin Temperature–vacuum swing adsorption
CO_2 source	air
Approach & System Boundary	Approach: Comprehensive LCA for direct air capture via temperature–vacuum swing adsorption with six adsorbents. Environmental impacts of captured CO_2 from cradle-to-gate and from cradle-to-grave. Comparing the environmental impacts of six adsorbents Environmental impacts of the DAC plant construction Environmental impacts of capturing 1% of global annual CO_2 emissions System boundaries: cradle-to-gate: The system boundaries include all environmental impacts due to material and energy supply of the CO_2 capture process. The cradle-to-gate system boundaries exclude the subsequent application of CO_2, which determines if the CO_2 is re-emitted or permanently removed from the atmosphere. cradle-to-grave: two applications for the captured CO_2 as a renewable carbon source for synthetic fuels (for example,methane synthesis) and by assuming geological storage, as in CDR applications.
Scenarios / Samples	Samples Commercial direct air capture plants (Hinwil and Hellisheiði operated by Climeworks)
Capacity	The plant capacity is 4 ktCO_2/yr. 3,683 DAC plants with a capacity of 100,000tCO_2/yr is also assessed.
LCA:Assumptions, Methods	Carbon capture efficiency and carbon removal efficiency Carbon capture efficiency (%): $\eta CO_2{,capture} = (mCO_2{,captured} - CCcapture\ process) / mCO_2{,captured} \times 100$ Where $mCO_2{,captured}$: Amount of CO_2 in kilograms captured CCcapture process: climate change (CC) impact due to adsorbent production, construction, end of life and operation of the DAC plant $\eta CO_2{,capture}$: Carbon capture efficiency Carbon removal efficiency (%): $\eta CO_2{,removal} = (mCO_2{,captured} - -CCcapture\ process - CCstoring\ process) / mCO_2{,captured} \times 100$

	Where CCstoring process: climate impacts induced by storing CO2 in geological reservoirs ηCO2,removal: carbon removal efficiency
Unit	kgCO2e per kgCO2 captured
LCA: CO2 NETS	Required DAC Capacity: * Capturing 1% of the global annual CO2 emissions in 2019 will require 3,683 DAC plants with a capacity of 100,000 tCO2/yr per plant. Carbon footprints of captured CO2 from cradele-to-grave are shown in Fig. 5
LCA: Other CO2-related results	carbon capture efficiency: *Hellisheiði: 93.1% Hinwil: 85.4% Footprint: The area occupied by the 3,683 DAC plants:29 km2. Wind power for DAC: additional 445 km2 PV for DAC: addisional 4,450 km2 Benefit od DAC and Environmental Impacts: The benefit of capturing 1% global CO2 emissions has to be weighed against the increase in other environmental impacts. This increase, however, is much smaller than 1% for most environmental impacts: the largest relative increase is 0.057% for human toxicity (cancer), which is an impact category with very high uncertainty (quality level II/III). The other impacts increase mainly due to the adsorbent (4.8–84.3%) and electricity supply via wind power (0–92.1%).
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 21

Year	2021
Title	Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources
Author (main)	Tom Terlouw et al.
Country	Switerland
Type of Analysis	Life-cycle Assessment of DACCS
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	No
Type of NETS	DACCS
Emission:Negative or Avoided	Negative Emission
Separation technology	solid sorbents with a lowtemperature regeneration (~100 ℃). DAC plant (based on Climeworks' technology)
CO2 source	Air
Approach & System Boundary	Approach: Detailed and transparent LCA of a lowtemperature potential DACCS system, based on Climeworks' technology and verified with the available data on low-temperature DAC, with different electricity (i.e., grid and photovoltaics (PV) power) and heat sources (i.e., electricity, waste, and solar heat) for CO2 capture. System Boundary: * DAC plant production to CO2 injection Our study aims at quantifying the net carbon removal efficiency of DACCS under different boundary conditions and in various system layouts, as well as at identifying potential environmental trade-offs coming along with CO2 removal.
Scenarios / Samples	Scenarios: Electricity from the grid, heat from a waste heat source. Electricity from the grid, heat from a HTHP operated with electricity from the grid. Electricity from a PV installation, heat from a Fresnel solar-thermal heat collector. Electricity from a PV installation, heat from a HTHP operated with electricity from a PV installation. Electricity from a PV installation, heat from a waste heat source. System: Autonomous (Fresnel solar heat systems + PV) Autonomous (high-temperature heat pump + PV) High-temperature heat pump + Grid Waste Heat + Grid Waste Heat + PV + Battery
Capacity	Capture: 100 ktCO2/yr
LCA: Assumptions, Methods	Main parameters per DACCS Configuration is shown in Table 1. * capture capacity: 100 ktCO2/yr * lifetime: 20 years * electricity consumption: 690 / 1271 / 1132 / 614 / 690 kWh/tCO2 captured (for Fresnel + PV / HTHT + PV / HTHP + Grid / Waste Heat + Grid / Waste Heat + PV + Battery) * waste of Fresnel heat consumption: 1500 / 0 / 0 / 1500 / 1500 kWh/tCO2 captured * sorbent consumption: 3.0 We define the carbon removal efficiency as "The share (in percentage) of net permanent GHG removal—"net" is the gross minus indirect (LCA related) emissions—of the initial gross GHG removal (100%) by the DAC unit".

Unit	% functional unit is defined as the "gross removal of 1 ton CO2 from the atmosphere via the use of a DAC plant combined with geological CO2 storage"
LCA: CO2 NETS	Figure 2. Life cycle GHG emissions in kg CO2-eq. per ton of gross CO2 removal with the DAC plant as well as carbon removal efficiencies [%] for different system layouts in selected countries.
LCA: Other CO2-related results	Figure 4 illustrates the overall environmental burdens and trade-offs for a selection of DACCS configurations and environmental impact categories.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 22

Year	2021
Title	Life cycle assessment of carbon dioxide removal technologies: a critical review
Author (main)	Tom Terlouw et al.
Country	Switzerland
Type of Analysis	LCA Critical review
Target/Calculation/Measurement	Assessment
LCA	Yes
TEA	No
Type of NETS	Afforestation and reforestation (AR) Biochar Soil carbon sequestration (SCS) Ocean fertilisation (OF) Bioenergy with carbon capture and storage (BECCS) Direct air carbon capture and storage (DACCS)
Emission: Negative or Avoided	Negative Emission
Separation technology	-
CO2 source	Atmosphere
Approach & System Boundary	Not mentioned
Scenarios / Samples	Not mentioned
Capacity	Not mentioned
LCA:Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Recommendation on LCA To improve the understanding of environmental implications of CDR deployment, we recommend to conduct LCAs with multiple environmental impact categories, to consider the temporal aspect of emissions in biomass-related CDR technologies, to focus on so far overlooked CDR technologies, to be as transparent as possible regarding methodological choices, to capture environmental side-effects, and to distinguish between 'avoided emissions' and 'negative emissions' – only negative emissions correspond to permanent removal from the atmosphere.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 23

Year	2021
Title	Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment
Author (main)	Kavya Madhu et al.
Country	Germany
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	No
Type of NETS	DACCS
Emission: Negative or Avoided	Negative Emission
Separation technology	temperature swing adsorption (TSA) high-temperature aqueous solution (HT-Aq) TSA: temperature vacuum swing adsorption HT-Aq: high-temperature aqueous solution
CO2 source	ambient air
Approach & System Boundary	The system boundary includes the material and energy input required for the production, operation and end-of-life treatment of the DAC air contactor, sorbent material and other auxiliary infrastructure required to capture CO2 from ambient air and store it in a geological sink. Transportation of materials, components and waste are also included. The exchange between the product system and the natural environment includes resource use and emissions to the environment relevant for the impact categories listed below.
Scenarios / Samples	HT-Aq DAC: A scale-up scenario was drafted that represents the infrastructure and energy requirements of an increase of the capacity from 345 t to 1 Mt CO2 captured per year. TSA DAC: A scale-up scenario was drafted to estimate the infrastructure, energy and material requirements of a transition from 50 to one million t CO2 captured per year. Since the Climeworks TSA DAC units are modular43, the 1 Mt scale up simply consists of approximately 20,000 TSA DAC units in standard containers as modelled in the reference case.
Capacity	a scale-up of the two technologies to a capture capacity of 1 Mt yr-1 and then linearly on to 1 Gt of CO2 captured per year LCA of the current pilot plans: 345 tCO2/yr (HT-Aq) 50 tCO2/yr (TSA) prospective LCA for a scale-up and technology learning scenario: CO2 capture capacity of 1 MtCO2/yr, followed by a linear scale-up to 1 GtCO2/yr
LCA: Assumptions, Methods	Life-cycle carbon capture efficiency (CCE): CCE (%) = 100 × -Life-cycle GHG / CO2 captured where Life-cycle GHG = GHGManuf + GHGoperation +GHGEoL - CO2 captured carbon capture rate (share of CO2 absorbed from air passing through): HT-Aq DAC: 42% / 47% / 25% / 70% (for Reference case / Best case / Worst case / Scale up) TSA DAC: 90% / 100% / 70% / 90%
Unit	MtCO2 GtCO2 The functional units for this study are 1 ton of CO2 captured and stored for the attributional LCA
LCA: CO2 NETS	CCE are shown in Supplementary table 3: Different energy mixes used to conduct LCA for different scenarios and sensitivity cases along with their respective Carbon capture efficiency (CCE).
LCA: Other CO2-related results	Comparison of TSA and HT-Aq

	TSA DAC outperforms HT-Aq DAC by a factor of 1.3–10 in all environmental impact categories studied.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned

Article 24

Year	2022
Title	BEST PRACTICES FOR LIFE CYCLE ASSESSMENT (LCA) OF DIRECT AIR CAPTURE WITH STORAGE (DACS)
Author (main)	Greg Cooney (US DOE)
Country	USA
Type of Analysis	specific guidance for implementation of the ISO standards to DACS systems
Target/Calculation/Measurement	-
LCA	Yes
TEA	Yes
Type of NETS	DACS
Emission: Negative or Avoided	(Carbon Negative Shot 関連から)Negative Emission
Separation technology	examples based on the sorbent and solvent pathways (the principles discussed could be generically applied to any engineered DACS system)
CO2 source	ambient air atmospheric CO2
Approach & System Boundary	Purpose: To support US DOE's Carbon Negative Shot initiative Complement to, not a replacement for, the ISO 14040/14044 to address issues that are specific to applications of those standards to DACS analysis. Functional units: Mass of CO2 captured Mass of CO2 captured from the atmosphere Mass of CO2 captured from the atmosphere and permanently stored Mass of net CO2e captured from the atmosphere and permanently stored gate-to-gate, cradle-to-gate, cradle-to-grave DACS systems necessarily require a cradle-to-grave boundary to achieve the stated function of CO2 removal.
Scenarios / Samples	Four performance elements: Less than $100/net metric ton CO2e for both capture and storage. Robust accounting of full life cycle greenhouse gas emissions. High-quality, durable storage with costs demonstrated for monitoring, reporting and verification for at least 100 years. Enables necessary gigaton-scale removal. To put this into perspective, one gigaton of CO2 is equivalent to the annual emissions from the U.S. light-duty vehicle fleet. This is equal to approximately 250 million vehicles driven in one year.
Capacity	Not mentioned
LCA: Assumptions, Methods	Life cycle inventory analysis Data collection: facility operation Data collection: non-consumables Data collection: consumables Data collection: key processes and potential data sources Co-product management Life cycle impact assessment The Life Cycle Impact Assessment (LCIA) Phase pertains to the translation of LCI emissions into potential environmental impacts based on the selection of a particular set of categories and characterization factors. While the primary focus in evaluating DACS and other CDR systems in an LCA context is the quantification of the net carbon dioxide (equivalents) removed from the atmosphere, LCA provides a basis for evaluating other potential environmental impacts allowing for an assessment of the potential tradeoffs between them. This more holistic view is how LCA differs from carbon footprinting.
Unit	net kg CO2e removed per functional unit kg CO2 per kWh of electricity

LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 25

Year	2022
Title	Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals
Author (main)	Tansu Galimova et al.
Country	Finland
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation
LCA	Yes
TEA	Yes
Type of NETS	e-fuel, e-chemicals
Emission: Negative or Avoided	Avoided Emission
Separation technology	Not mentioned
CO2 source	anthropogenic CO2 (industrial point sources: limestone fraction of CO2 emissions from cement mills, bio-CO2 emissions from pulp and paper mills, and CO2 from waste incinerators) Atmosphere
Approach & System Boundary	Approach: The study estimates the global demand for CO2 as raw material in the production of renewable electricity-based e-fuels and e-chemicals within an integrated energy-industry system based on 100% renewables enabling zero CO2 emissions by 2050. System Boundary: CO2 source, reactor (literature)
Scenarios / Samples	Model: LUT Energy System Transition Model Total energy demand for the power, heat, and transport sectors including industrial energy demand is extracted from the results for 2030 to 2050 (Bogdanov et al., 2021b). Demand for e-methane that is used in the power and heat sectors and e-kerosene jet fuel used in the transport sector is taken from Bogdanov et al. (2021b), while e-methanol demand for the chemical industry is derived according to the methods by Bogdanov et al. (2021a) and is taken from Ram et al.(2020).
Capacity	In 2040, DAC is projected to supply 1582 Mt of CO2 as raw material and 1659 Mt of CO2 is expected to be supplied by point sources globally. By mid-century, DAC meets 63% of global demand for CO2, thus supplying 3824 Mt of CO2 as demonstrated in Fig. 14.
LCA: Assumptions, Methods	Not mentioned
Unit	tCO2/toutput ktCO2/TWhth,waste €/tCO2
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	CO2 supply for E-fuel and E-chemicals: Key industrial point sources can potentially supply 2.1 gigatonnes of carbon dioxide and thus meet the majority of the demand in the 2030s. By 2050, however, direct air capture is expected to supply the majority of the demand, contributing 3.8 gigatonnes of carbon dioxide annually.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Levelised cost of CO2 from DAC (literature): In 2050, the levelised cost of CO2 from DAC is projected to be in the range of 38–71 €/tCO2 (Fasihi et al., 2019). This could be even lower at 32 €/tCO2, in case of free excess heat availability from industrial sources or when low temperature DAC units are integrated with e-fuels production (Fasihi et al., 2019). The costs of CO2 captured from industrial point sources in 2020 is in the range of 20–100 €/tCO2, and by 2050 the costs are projected to decline to around 12–25 €/tCO2 (Fasihi et al., 2019).
TEA: Other cost-related results	Not mentioned

Article 26

Year	2022
Title	Energetic and Life Cycle Assessment of Direct Air Capture: A Review
Author (main)	Junyao Wang et al.
Country	China
Type of Analysis	review
Target/Calculation/Measurement	review
LCA	Yes
TEA	No
Type of NETS	DAC, DACCS
Emission: Negative or Avoided	Negative Emission
Separation technology	-
CO2 source	atmosphere ambient air
Approach & System Boundary	Scope:The energetic and life cycle analysis studies are systematically reviewed for typical DAC technologies.Potential energetic approaches are identified and analyzed through key features to discuss their ability to address energy performance of DAC systems. LCA works are reviewed following standard LCA framework, which allows to critically and systematically analyzed individual steps of the assessment. Finally, the closely relationship between the energetic and carbon removal performance of DAC are discussed. This work will contribute to establishing a systematic energetic and life cycle assessment framework of DAC systems.
Scenarios / Samples	Systems (Literature): - HS (moisture swing adsorption)-DAC - LT-DAC - HT-DAC
Capacity	-
LCA: Assumptions,Methods	Not mentioned
Unit	t/year
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Summary of energy consumption of HT DAC - Heat: 4.5-8.9 GJ/t Electricity: 366-764 kWh/t Summary of energy consumption of LT DAC - Heat: 0.29-11.8 GJ/t Electricity: 150-694 kWh/t
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 27

Year	2022
Title	Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100
Author (main)	Yang Qiu et al.
Country	USA, the Netherlands, Germany, Switzerland
Type of Analysis	Assessment
Target/Calculation/Measurement	Calculation of prospective LCA of DACCS
LCA	Yes
TEA	No
Type of NETS	DACCS
Emission: Negative or Avoided	Negative Emission
Separation technology	DACCS/solvent-based DACCS/sorbent-based DACCS
CO2 source	ambient air/Atmosphere
Approach & System Boundary	Approach: Across 26 global regions based on the demographic, economic, technological and behavioral narratives of the Shared Socioeconomic Pathways (SSP2). Here, we calculate a prospective LCA of DACCS under climate change mitigation scenarios developed by the IMAGE 3.2 Integrated Assessment Model. The system boundary starts at the air inlet with a CO2 concentration of 415 ppm, and is followed by CO2 capture, regeneration, compression, transport, and ends with geological storage.
Scenarios / Samples	Scenarios solvent-based DACCS with biomethane (SV + BM) solvent-based DACCS with natural gas (SV + NG) sorbent-based DACCS with biomethane (SB + BM) sorbent-based DACCS with heat pump (SB + HP) SSP2-RCP1.9 w/ DACCS: the US electricity sector achieves a full decarbonization by 2035 (Fig, 2d), which is in-line with current targets and an economy-wide decarbonization by 2050. The scenario features an earlier phase-out of coal and natural gas (by 2050) and higher renewable energy penetration (81%) by 2100 (Fig. 2c). We assume a commercial-scale operation and technology improvements via learning-by-doing.
Capacity	DACCS deployment in the US starts around 2050, and its annual operational capacity reaches 0.85 GtCO2/year by 2100
LCA: Assumptions, Methods	Models: IMAGE 3.2 Integrated Assessment Model we adapt an open-source LCA framework37,38 to modify electricityrelated data in the background LCI database using regionally and temporally explicit IMAGE projections (on electricity mix, generation efficiency, and electricity-associated emissions) from 2020 to 2100 under the three scenarios
Unit	per 1tatmospheric CO2 captured and sequestered
LCA: CO2 NETS	—
LCA: Other CO2-related results	As for other non-climate metrics, sorbent-based DACCS generally exhibits higher impacts in human toxicity, freshwater eutrophication and ecotoxicity, and metal depletion mainly due to its higher unit electricity consumption. In contrast, solventbased DACCS shows a higher water depletion (per 1 t CO2 captured, 3–12 times more than sorbent-based DACCS), because it captures CO2 using an aqueous hydroxide solution, which evaporates during the operation, while sorbent-based DACCS uses solid amine-based sorbents, which consumes much less water during the production and use phases.
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 28

Year	2023
Title	Carbon capture and utilization: More than hiding CO2 for some time
Author (main)	Jan Mertens et al.
Country	France, Belgium, Germany, Italy, Portugal, the Netherlands, USA
Type of Analysis	Analysis Commentary
Target/Calculation/Measurement	Not mentioned
LCA	No
TEA	No
Type of NETS	DAC DACCU
Emission: Negative or Avoided	Avoided Emission
Separation technology	solid sorbent-DAC liquid sorbent-DAC Two major commercial DAC processes are currently available: high temperature using an aqueous solution and low temperature using a solid sorbent.
CO2 source	Air
Approach & System Boundary	Not mentioned
Scenarios / Samples	Not mentioned
Capacity	Not mentioned
LCA:Assumptions, Methods	Not mentioned
Unit	Not mentioned
LCA: CO2 NETS	Not mentioned
LCA: Other CO2-related results	Not mentioned
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

Article 29

Year	2025
Title	How do ambient conditions influence sorbent selection in adsorption-based direct air capture?
Author (main)	Malte Glaser (co-authors: Arvind Rajendran, Sean T. McCoy)
Country	Canada (CanCO2Re project; Government of Canada funding)
Type of Analysis	Time-dependent 0-D process modeling, validation against a 1-D model, and single-objective optimization of sorbent selection under weather-dependent inputs
Target/Calculation/Measurement	Quantify how hourly-varying ambient conditions (temperature, humidity) influence optimal sorbent selection; compute Pr (productivity), SED (specific energy demand), RR (removal rate), CRE (carbon removal efficiency), and CRR (net carbon removal rate); model CO2/H2O co-adsorption via mass/energy balances and LDF kinetics in a TVSA cycle
LCA	No full LCA; on-site energy-related GHG emissions included via an emission factor (assumed natural gas) to derive CRE and CRR
TEA	Not performed (no costs, CAPEX/OPEX)
Type of NETS	DACCS
Emission:Negative or Avoided	Negative (focus on removal; CRR maximization accounts for on-site emissions)
Separation technology	Adsorption-based DAC; temperature–vacuum swing adsorption (TVSA) with optional steam; sorbents: APDES-NFC-FD-S (chemisorbent), SIFSIX-18-Ni-β and NbOFFIVE-1-Ni (physisorbents)
CO2 source	Ambient Air
Approach & System Boundary	Single cylindrical contactor modeled as a well-mixed reactor (0-D); includes fan power, vacuum pump, heating jacket, optional steam generation; calibrated against a published 1-D model to match Pr and SED trends; operational boundary limited to contactor and utilities; excludes construction/material manufacturing and full supply-chain impacts
Scenarios / Samples	Four ambient-condition input scenarios: Actual (8760 h), Temporally aggregated typical periods (TPs), Resampled (20-hour intervals; 438 h), Averaged (year-average); case studies: Calgary (cold/dry, highly variable) and Barbados (warm/humid, stable); plus artificial ambient-condition grid covering wide T–RH–variation ranges
Capacity	Fixed single-column geometry (per-adsorber performance); no industrial scaling within this study
LCA: Assumptions, Methods	On-site GHG emission factor eenergy,CO2,eq = 0.184 kg/kWh (0.0511 kg/MJ), assumed natural gas; primary energy accounting with 50% thermal-to-electric conversion efficiency; CO2 purity constraint >95%; CRE and CRR definitions used for optimization
Unit	Typical units: kWh/tCO2, MJ/kgCO2, mol, K, Pa, m/s, s, kg/kWh (or kg/MJ) for emissions
LCA: CO2 NETS	Net carbon removal rate (CRR) and carbon removal efficiency (CRE) reported; NbOFFIVE yields negative CRR in Calgary (not recommended); optimal sorbent is sensitive to on-site emission factor (e.g., >0.24 kg/kWh can shift Calgary's optimum to APDES)
LCA: Other CO2-related results	CRR can vary up to ~476% across locations/sorbents; SED varies up to ~159%; strong dependence on ambient averages and variability (diurnal/seasonal), cautioning against fixed benchmark KPIs
TEA: Assumptions & Methods	Not mentioned
TEA: CAPEX	Not mentioned
TEA: OPEX	Not mentioned
TEA: Cost of product(s)	Not mentioned
TEA: Other cost-related results	Not mentioned

MISSION INNOVATION

Mission Innovation – Catalyzing Clean Energy Solutions For All