THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Opportunities for Direct Air Capture Technologies

SINA HOSEINPOORI

Department of Environmental and Energy Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

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SINA HOSEINPOORI
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Department of Environmental and Energy Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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SINA HOSEINPOORI
Department of Environmental and Energy Sciences
Chalmers University of Technology

Abstract

In 2024, the mean global temperature exceeded the 1.5 °C limit for the first time, highlighting the increasing likelihood that greenhouse gas emissions will significantly overshoot the limits set by the Paris Agreement. Thus, technologies for carbon dioxide removal (CDR) are crucial for limiting global warming to well below 2°C. Among the CDR technologies, Direct Air Capture (DAC) has gained attention due to its scalability and potential for placement in proximity to storage sites. However, DAC remains a relatively costly option for CO_2 removal, mainly because of its substantial energy requirements due to the low concentration of CO_2 in the atmosphere. This, together with its relatively low levels of technical maturity make its deployment marginal so far.

This thesis first compares the different DAC technologies in terms of energy and exergy, to assess how material use influences overall technology performance. Thereafter, the thesis investigates three alternative deployment opportunities for the two DAC technologies that have the highest technology readiness levels: Temperature Vacuum Swing Adsorption (TVSA) and Alkaline Absorption with subsequent Calcium Looping (ALK-ABS). The studied opportunities entail: (I) using DAC for capturing CO_2 from low-concentration (<4% CO_2) flue gas streams; (II) using DAC as a second CO_2 capture step after scrubbing using monoethanolamine (MEA) from high-concentration (>4% CO_2) flue gas streams, so as to achieve net-zero direct emissions; and (III) integrating DAC into combined heat and power (CHP) plants. The work combines modeling at the process and reactor levels to close the mass and heat balances, and the use of these results in a techno-economic modeling framework for calculating the costs of carbon capture and carbon avoidance.

The exergy analysis indicates that adsorption-based DAC processes have greater overall exergy efficiency than the absorption-based process. Moreover, the findings highlight the importance of material stability and degradation for overall process performance: material consumption represents around 5%–10% of the total exergy demand for absorption-based DAC systems, and the corresponding range for the adsorption-based process is 10%–40%.

Regarding the use of DAC for capturing CO_2 from dilute flue gas streams (I), the modeling results reveal that MEA scrubbing has a better economic performance than TVSA or ALK-ABS when the flue gas flowrate exceeds 200 t/h. For lower flowrates (especially those <100 t/h), TVSA is the most cost-effective option under the conditions studied, and ALK-ABS is only cost-efficient for a narrow range of flowrates of 100–200 t/h and CO_2 concentrations of 0.5%–1.2%. Furthermore, for such low flowrates and CO_2concentrations <2%, the carbon avoidance cost is higher than offsetting CO_2 at the current market prices for CDR credits (here considered to be in the range of 400–600 \$/tCO_2).

The use of DAC as a second step (after MEA scrubbing) in the capture sequence for high-CO_2-concentration flue gases (II) has been compared with the combination of CCS and offsetting of residual emissions through CDR credits, as well as with the operation of CCS at a capture rate that is sufficiently high to achieve net-zero emissions directly. The hybrid solution is shown to involve lower overall costs to achieve net-zero direct emissions than the other two strategies studied. Furthermore, it is found that the alternative of offsetting residual emissions externally achieves its optimal overall capture cost when MEA scrubbing is operated at a capture rate of approximately 99%, i.e., far higher than the typically used benchmark value of 90%.

Finally, it is found that integrating DAC into CHP plants (III) presents a viable business opportunity, particularly in the emerging CDR market. When taking as the credit value a future cost projection for DAC of 680 \$/tCO_2, CDR could contribute up to 80% of the net cash flow of CHP plants in the future, with DAC alone accounting for 12%. Further estimates suggest that integrating DAC into CHP plants across Sweden could meet approximately 33% of the country's national CDR target.

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. Hoseinpoori S, Pallarès D, Johnsson F, Thunman H.
A comparative exergy-based assessment of direct air capture technologies.
Mitigation and Adaptation Strategies for Global Change, 2023, 28(7):39.

II. Hoseinpoori S, Roshan Kumar T, Beiron J, Johnsson F, Svensson E, Pallarès D.
Integration of Sorbent-Based Direct Air Capture into Combined Heat and Power Plants with Post-Combustion Carbon Capture.
Energy, 2025, 328, 0360–5442 136509.

III. Hoseinpoori S, Johnsson F, Pallarès D.
Capture or offset: Techno-economic evaluation of mitigating emissions from industries with flue gas streams containing low CO_2 Concentrations.
Submitted for publication.

IV. Hoseinpoori, S., Pallarès, D., Roussanaly, S., Riboldi, L., Subraveti, S.G., Donghoi, K, Anantharaman, R., Johnsson, F.
Designing for Net Zero: Cost-Optimal Capture Rates and the Emerging Role of Direct air capture.
To be submitted.

Sina Hoseinpoori is the principal author of all the papers listed.
Professor David Pallarès contributed with discussions, methodology development, and editing of **Papers I–IV**.
Professor Filip Johnsson contributed with discussions and editing of **Papers I–IV**.
Professor Henrik Thunman contributed with discussion of **Paper I**.
Dr. Tharun Roshan Kumar contributed with discussions, methodology development, and editing of **Paper II**.
Dr. Johanna Beiron contributed with discussions and editing of **Paper II**.
Associate Professor Elin Svensson contributed with discussion and editing of **Paper II**.
Dr. Rahul Anantharaman contributed to the conceptualization, methodology, discussion and editing of **Paper IV**.
Dr. Simon Roussanaly contributed to the conceptualization, methodology, discussion and editing of **Paper IV**.
Dr. Luca Riboldi, contributed to the conceptualization, methodology, discussion and editing of **Paper IV**.
Dr. Sai Gokul Subraveti contributed to the conceptualization, methodology, discussion and editing of **Paper IV**.
Dr. Donghoi Kim contributed with methodology, discussion and editing of **Paper IV**.

Other publications not included in this thesis

- Vering C, Engelpracht M, Göbel S, Hoseinpoori S, Wüllhorst F, Schwenzer C, Rademacher M, Hinrichs S, Chandra F, Mehrfeld P, and Müller D
  Open-Source vapor compression library (VCLib): Heat pump modeling for education and research,
  Comput. Appl. Eng. Educ. 2022, 30:1498–1509.

- Postweiler P, Wiederhoeft T, Rezo D, Engelpracht M, Nilges B, Hoseinpoori S, Wedler C, and von der Assen N. Enhancing DACCS Flexibility: Evaluating Hardware Modifications for Cost-Effective Carbon Dioxide Removal.
  Submitted for publication.

“There is no free lunch in thermodynamics”

Second law of thermodynamics

“Do our best remove the rest”

Mischa Repmann

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زندگی صحنه ی یکتای هنرمندی ماست
هر کسی نغمه ی خود خواند و از صحنه رود
صحنه پیوسته به جاست
خرم آن نغمه که مردم بسپارند به یاد

Sina Hoseinpoori
سینا حسین‌پوری

28th April 2026
سه شنبه ۸ اردیبهشت ۱۴۰۵

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Declaration on the use of generative AI in the writing process

During manuscript preparation, AI tools like ChatGPT and Claude aided in writing and editing. They helped refine language, enhance clarity and conciseness, and standardize terminology based on author-provided content. It did not create original scientific ideas, data, or conclusions. All scientific content and decisions were made, verified, and approved by the author. The author is fully responsible for the manuscript's accuracy and integrity.

Table of Contents

Nomenclature

Abbreviations and Acronyms

Symbol / Abbreviation	**Description**
ALK-ABS	Alkaline Absorption with subsequent Calcium Looping
BECCS / BioCCS	Bioenergy with Carbon Capture and Storage
CAC	Carbon Avoidance Cost
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
COC	Cost of Capture
COP	Coefficient of Performance
CR	Capture Rate
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
EU	European Union
FOAK	First-of-a-Kind
L-DAC	Liquid-Sorbent Direct Air Capture
MEA	Monoethanolamine
MOF	Metal-Organic Framework
NCF	Net Cash Flow
NGCC	Natural Gas Combined Cycle
NOAK	Nth-of-a-Kind
ORC	Organic Rankine Cycle
PCC	Post-Combustion Capture
PEI	Polyethylenimine
RQ	Research Question
S-DAC	Solid-Sorbent Direct Air Capture
TCR	Total Capital Requirement
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
TVSA	Temperature Vacuum Swing Adsorption

Latin Symbols

$C_{fixed\ O\&M}$	Fixed Operation and Maintenance Cost
C_{inv}	Capital Investment Cost
$C_{variable\ O\&M}$	Variable Operation and Maintenance Cost
$C_{T\&S}$	Cost of CO_2 Transportation and Storage
CR	Capture Rate
Ex_{ch}	Chemical Exergy
$m_{CO2,\ avoided}$	Mass of CO_2Avoided
$m_{CO2,\ captured}$	Mass of CO_2 Captured
$m_{CO2,\ chem}$	Indirect CO_2 Emissions from Chemical Consumption
$m_{CO2,\ elec}$	Indirect CO_2 Emissions from Electricity Use
$m_{CO2,\ heat}$	Indirect CO_2 Emissions from Heat Supply
Q_{in}	Heat Input
T_{bf}	Temperature of bulk flow
T_{env}	Ambient Temperature
$W_{min,CO2}$	Minimum Thermodynamic Work for CO_2 Separation
EL_{in}	Electricity Input

Greek Symbols

η_{I}	First-Law Efficiency
η_{II}	Second-Law Efficiency
η_{ex}	Exergy Efficiency

Chemical Species

$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CO_2	Carbon Dioxide
H_2O	Water
K_2CO_3	Potassium Carbonate
KOH	Potassium Hydroxide
MEA	Monoethanolamine
NaOH	Sodium Hydroxide

Introduction

The atmospheric concentration of greenhouse gases has been increasing steadily since the beginning of the industrial revolution, mainly due to increasing anthropogenic emissions[1]. More specifically, the atmospheric concentration of CO_2 has increased from 315 ppm in Year 1960 to 424 ppm in Year 2024[2]. As a result, the mean global surface temperature has risen by 1.5 °C above the pre-industrial level[3]. The Paris Agreement was signed in 2015, aimed at limiting the temperature increase to well below 2 °C by the end of this century. This corresponds to an atmospheric carbon budget that requires reaching net-zero CO_2 emissions by around Year 2050, which is the target for the European Union (EU)[4].

Limiting the increase of CO_2 in the atmosphere can be achieved by: avoiding the generation of CO_2 (by, for example, transitioning to renewable energy sources and reducing energy use); avoiding emissions (by, for example, capturing and storing or reusing CO_2); and removing CO_2 from the atmosphere. These different layers of mitigation are presented in Figure 1, which indicates the degrees of their urgency and cost. Each layer in the pyramid in Figure 1 facilitates the employment of the measures in the next layer up.

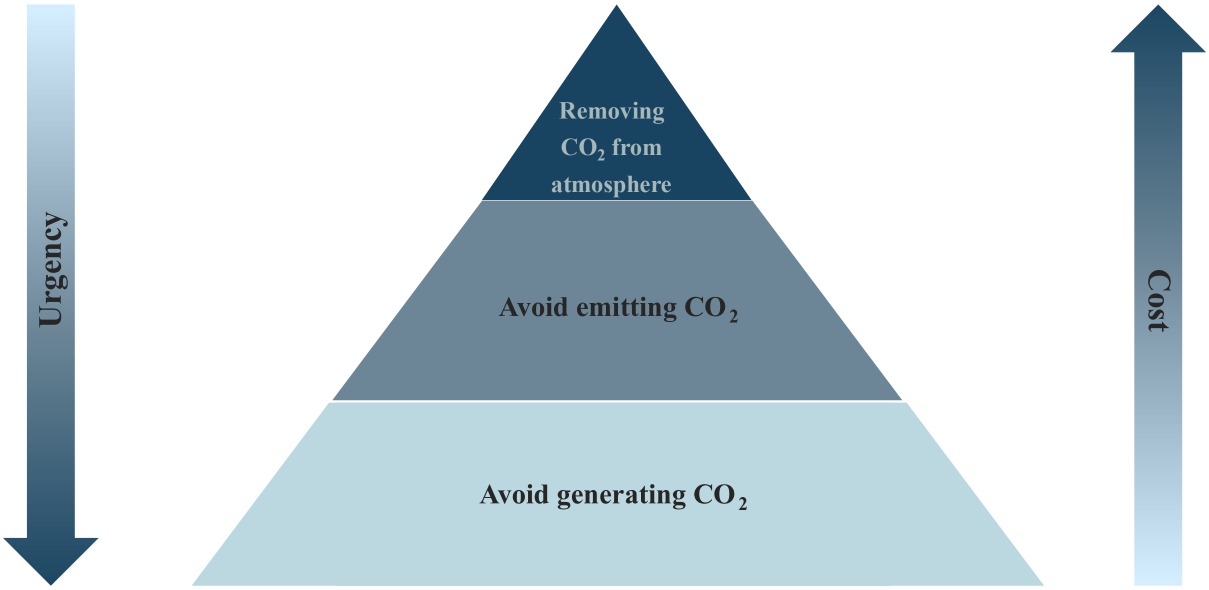


Figure 1: The pyramid of mitigation actions for achieving net-zero emissions from a system (not a single-plant) perspective based on cost and urgency (arrows indicate the directions of increase). Source: **Paper IV**.

A transition towards renewable energies would enable higher efficiencies of carbon capture processes, given that less indirect CO_2 is emitted during the capture process, leading to higher CO_2 avoidance rates. Furthermore, with successful mitigation of CO_2 emissions, the demand for carbon dioxide removal (CDR) could be restricted to those emissions that cannot be cut in other ways or are associated with high mitigation costs.

On the other hand, avoiding CO_2 emissions through the use of carbon capture and storage (CCS) processes would limit the demand for CDR to historical emissions and hard-to-abate emissions. While historical emissions are clearly defined, the term 'hard-to-abate' remains vague because a metric to evaluate which emissions are hard to tackle is lacking. For example, a large category of hard-to-abate emissions involves industrial residual emissions defined as the emissions that remain after carbon capture has been applied to a flue gas stream. Although this definition presents a way to identify hard-to-abate emissions, it does not set a limit beyond which capturing is considered hard. Recently, the cost and exergy demand of direct air capture (DAC) has been proposed as a threshold metric beyond which abatement is considered hard[5].

Currently, total annual fossil CO_2 emissions to the atmosphere are 37.8 Gt[6]. These are the emissions that need to be mitigated to reach the net-zero target set by Year 2050. Without significant and immediate cuts in these emissions, the relevant carbon budget is unlikely to be met, resulting in an emissions overshoot and, thus, the need for CDR[7]. Various CDR methods have been proposed in the literature.

Figure 2 shows the main CDR methods[8]:

- **Afforestation/Reforestation:** Removal of CO_2 through either restoring previously deforested areas or planting trees in previously unforested areas.
- **Soil carbon sequestration: S**oil carbon sequestration is the process of transferring atmospheric CO_2 into the soil through plants, plant residues, and microorganisms, storing it as soil organic carbon.
- **Biochar:** Permanent storage of carbon in the form of charcoal through the pyrolysis of biomass.
- **Enhanced weathering:** Artificial stimulation of the natural processes of minerals that involve reaction with CO_2 in the air to form carbonate minerals on land or in oceans.
- **Bioenergy with carbon capture and storage (BECCS/BioCCS):** A group of technologies that capture CO_2 from stacks at large point sources, such as power plants and industrial processes (e.g., pulp and paper mills) using biomass as feedstock, followed by permanent storage of the CO_2 in geologic formations located deep underground.
- **Direct air carbon capture and storage (DACCS):** Technologies that capture CO_2 from the air through a chemical process and then store it permanently
- **Ocean fertilization:** Ocean alkalinization is an approach to carbon removal that involves adding alkaline substances to seawater in order to enhance the ocean's natural carbon sink.

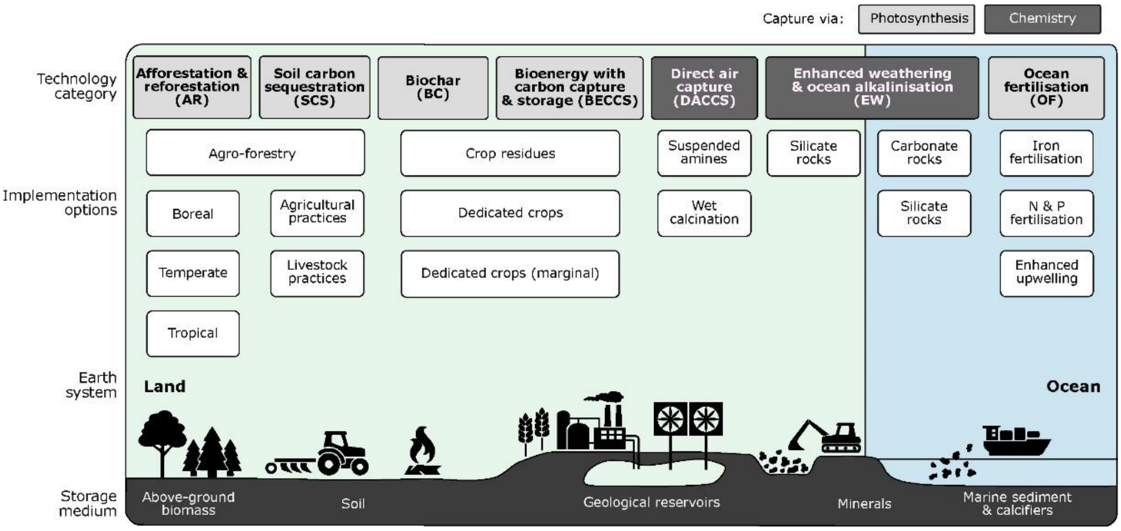


Figure 2: Different methods of carbon dioxide removal. Taken from Minx et al[8].

Direct air capture (DAC) and BioCCS output a high-purity stream of CO_2, which can be permanently stored to create CDR value (top layer of the pyramid in Figure 1) or converted to fuels or materials to contribute to limiting the increase in carbon mass above the ground (bottom layer of the pyramid in Figure 1). BioCCS offers CDR at a lower cost than DAC due to the higher concentration of CO_2 in flue gases compared to atmospheric air, as well as the co-generation of heat and power that it offers alongside CDR. However, the scalability limited by biomass availability and the measurability of CDR remain as concerns. DAC addresses these issues by providing CDR that is both scalable and measurable. The primary obstacle to the large-scale deployment of DAC is its high net removal cost, which is dominated by three key factors:

- High energy demand: Energy requirements can only be reduced through technological advancements and process integration. This requires research on process optimization and/or integration with other industrial processes.
- Significant capital investment: The large capital investment required for DAC technologies can be reduced through further deployment, allowing the technology to progress along the learning curve.
- Indirect emissions from the DAC chain: The impact of indirect emissions can be mitigated by using renewable energy sources to power DAC operations. As a result, recent literature has increasingly focused on evaluating DAC performance under different energy supply scenarios.

This underscores the importance of strategic DAC deployment to reduce the net removal cost, which involves three key considerations.

1. Geographic location

    The location of DAC influences several factors that impact on the net removal cost:

    1. Climatic conditions (e.g., temperature, relative humidity, wind), which affect the energy requirements of the process[9–11].
    2. Prices and carbon footprints of different energy sources, which influence DAC's operational expenditure[12–18].
    3. Access to infrastructure for CO_2 transport and storage, which influences the cost based on distance and type of transport[19].

2. Multi-functionality

    DAC is generally designed to generate CDR as the sole product; therefore, all costs are allocated to CDR, contributing to its high removal cost. Designing DAC systems with multiple products may provide a means to reduce the cost of CDR. Approaches include storing the captured CO_2 in minerals in the form of bricks[20] or cementitious materials[21], co-removing rare gases such as krypton and xenon[22], and providing water as a secondary product[22,23]. While these approaches yield tangible products, the potential also exists for DAC to provide intangible products and services, such as indoor air quality enhancement when integrated into ventilation and air-conditioning systems, where the CO_2 concentrations are higher than in ambient air[24–27].

3. Diversification of the application

    While DAC was originally developed for CO_2 removal from ambient air, it can also be considered as a gas separation technology that is optimized for gas streams with low CO_2 concentrations. Advancing beyond the traditional DAC application could unlock new use cases based on the technology's core attributes rather than its input stream. This broader application potential could drive additional demand, further accelerating technology development and deployment and, thereby, helping to lower capital costs along the learning curve.

This thesis focuses specifically on investigating the roles of alternative applications of DAC technologies as pathways to reduce net removal costs or enhance deployment potential.

1.1 Aim

The overarching aim of this thesis is to explore alternative opportunities for the deployment of DAC technologies. In this thesis, a deployment opportunity for DAC technologies refers to conditions under which DAC or DAC-derived solutions are technically feasible and economically competitive for CO_2 removal or provide system-level advantages compared with alternative mitigation strategies. Such conditions arise when DAC can meet an existing market demand for carbon removal or when its implementation results in lower mitigation costs or improved profitability. This definition focuses on the direct implementation of DAC systems, while the analysis also considers contexts in which DAC technologies are applied for uses other than conventional carbon removal, as well as enabling conditions that support or accelerate their deployment. We use established methodologies from the literature to answer the following three research questions (RQs):

RQ I: Which conditions make integrating adsorption-based DAC into CHP plants linked to district heating networks, a viable pathway for DAC deployment? (Investigated in **Paper II**).

RQ II: What role can DAC or DAC-derived technologies play in mitigating direct emissions from industries with CO_2-rich (>4%) flue gases? (Investigated in **Paper III**).

RQ III: What role can DAC or DAC-derived technologies play in complementing CCS in industries with CO_2-lean (<4%) flue gases? (Investigated in **Paper IV**).

1.2 Scope

This thesis focuses on adsorption- and absorption-based DAC, which are the most-developed DAC technologies that have reached commercial deployment. The analysis of adsorption-based DAC is limited to temperature vacuum swing adsorption (TVSA), and for absorption-based DAC it is limited to alkaline absorption with subsequent calcium looping (ALK-ABS), as these two processes exhibit the highest technology readiness levels and their greater data availability facilitates modeling.

To generalize and streamline the cost assessment, the work focuses on the capture step which means that the upstream costs and emissions associated with the plant generating the target flue gas are excluded, and the costs for CO_2 transport and storage are simplified.

1.3 Thesis outline

The thesis consists of this introductory essay and four appended papers. Beyond this introduction (Chapter 1), this introductory essay is structured as follows:

Chapter 2 presents the technological background based on **Paper I**, along with a summary of previous works.

Chapter 3 summarizes the methodology used to answer the identified research questions, based on the detailed descriptions provided in **Papers II–IV**.

Chapter 4 summarizes and discusses the main results related to the research questions addressed, based on **Papers II–IV**.

Chapters 5 and **6** draw conclusions from the work and suggest future work, respectively.

Paper I provides a review of the different DAC technologies and compares them from an exergy point of view, to evaluate the impact of material consumption on their overall system performance.

Paper II evaluates the plant-scale economics of integrating DAC into a CHP plant that provides district heating.

Paper III evaluates the use of DAC-derived technologies, originally designed for atmospheric carbon capture, for point-source capture in industries that are emitting low- CO_2-concentration flue gas streams and targeting net-zero direct emissions. The assessment is carried out for a range of inlet flowrates (25–2,700 t/h) and CO_2 concentrations (0.5%–4%).

Paper IV explores the potential roles of DAC and DAC-derived technologies in mitigating direct emissions from industries that are emitting high- CO_2-concentration flue gas streams and targeting net-zero direct emissions. The assessment is carried out using a constant flowrate (10,600 kmol/h) and a range of concentrations (4%–20%).

Technical background

Direct air carbon capture and storage processes comprise the following four main steps[28], as depicted in Figure 3:

1. Direct Air Capture by circulation of air through a sorbent for the removal of CO_2, followed by regeneration of the sorbent and release of CO_2.
2. CO_2 conditioning (e.g., liquefaction for transport).
3. Transportation of CO_2 to the sequestration location.
4. Storage of CO_2.

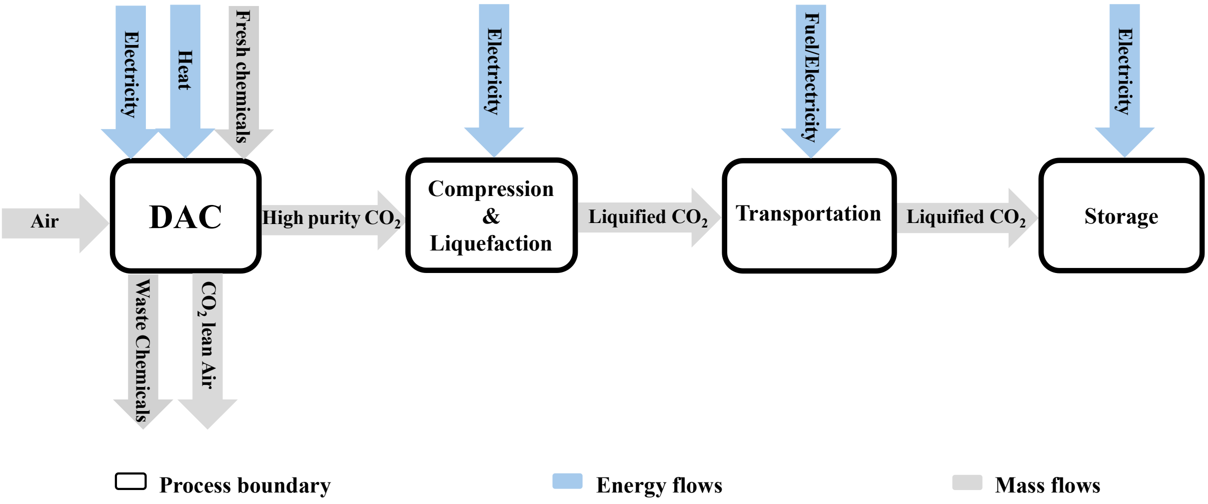


Figure 3: Flowchart for CDR via DACCS.

As a gas separation technology, DAC is commonly compared to carbon capture and storage (CCS). Table 1 outlines the differences between CCS (via MEA absorption, the benchmark technology) and DAC, with an important distinction being that CCS captures CO_2 from flue gas streams (thereby generating carbon avoidance and the possibility to contribute to CDR if the carbon in the flue gas stream is biogenic in origin), whereas DAC removes CO_2 from the atmosphere (hence, inherently generating CDR). Furthermore, the sizing and location of CCS units is governed by the emissions source, while DAC can be optimized according to different parameters[29], such as weather, access to energy, infrastructure, and carbon storage. For DAC, flexibility of location also decouples its deployment from heavy investments in transport infrastructure by enabling siting near storage facilities. In addition, DAC deployment does not interfere with emissions source location or operation, so it is not subject to the space constraints associated with point-source capture[29].

Since the concentration of CO_2 in flue gas streams is 2–3 orders of magnitude higher than in atmospheric air, the minimum thermodynamic work for the separation of CO_2 in a CCS application is 2–8-times less than for DAC. Thus, the predicted cost for DAC (110–835 \$/tCO_2) is a few times higher than for the corresponding capture stage of CCS (40–120 \$/tCO_2). The current costs for DAC and CCS are higher than these Nth-of-a-kind figures, since only a few plants have been brought into operation. Finally, it is noteworthy that since flue gases usually are at high temperature and contain sulfur oxides and nitrogen oxides, CCS requires cooling and gas cleaning prior to entry into the capture unit.

Table 1: Comparisons of the main characteristics of CCS (point source capture) and DACCS.

	CCS	**DACCS**
Technology readiness level	TRL 8–9[30]	TRL 6–7[31]
Inlet CO_2 concentration	4–20%vol	420 ppm (0.042%vol)
Product	CO_2 emissions avoidance (for fossil CO_2) or CDR (for biogenic CO_2)	CDR
Location	Bound to emission source	Result of cost optimization
Scale	Dependent upon emissions source	Dependent upon access to energy and infrastructure
Operation	Dependent upon flue gas conditions and composition	Dependent upon climate conditions
Prior gas cleaning	Required	Not required
Capture rate	90%–99%[32]	Strongly variable, result of the cost optimization
Minimum thermodynamic work requirement	2–9 kJ/mol CO_2 [33,34]	21 kJ/mol CO_2[35]
Current cost of avoidance/removal	Approx. 470 \$/tCO_2[36,37]	450–1,200 \$/tCO_2[38,39] As CDR credits
Predicted cost of capture	40–120 \$/tCO_2[40] (without transport and storage)	110–835 \$/tCO_2[41,42]

1.4 DAC processes

1.4.1 Absorption-based DAC

Absorption is the phenomenon whereby a gas molecule enters a liquid or solid sorbent material [43]. Absorption-based DAC uses an aqueous hydroxide solution as sorbent and is, therefore, commonly referred to as liquid DAC (L-DAC). The process is derived from the pulp and paper industry[44]. Therefore, the main components of this process have reached maturity. The process is comprised of two cycles, capture and regeneration[45], as well as four main components: air contactor, causticizer, calciner, and slaker, followed by a compression cycle (Figure 4). The initial designs also recommend a natural gas combined cycle as the power island, in order to meet the electricity demand of the process. An absorption column using potassium hydroxide (KOH) as the solvent is proposed to capture 90% of the emissions from the combined cycle flue gases. The outlet gas from the absorption column is mixed with the inlet air to the air contactor, and the outlet solvent is combined with the outlet stream of the air contactor.

I. Air contactor

In the air contactor, where the absorption process occurs, air is forced by a fan through a packing with KOH (or NaOH as alternative) solution[46]. The CO_2 is dissolved in the liquid phase to form carbonate ions, which then react with potassium ions to form potassium carbonate (K_2CO_3), according to Eq. (1):

$$2KOH_{(aq)} + CO_{2(g)} \rightarrow K_2CO_{3(aq)} + H_2O_{(l)} \qquad \Delta H = -95.8\ kJ/mol \qquad (1)$$

II. Causticizer

Since K_2CO_3 is highly soluble in water, the liquid carbonate solution is sent to a causticizer where it reacts with calcium hydroxide fines. During the reaction, the hydroxide solution is regenerated, and calcium carbonate crystals start to form around the calcium fines, according to Eq. (2). The causticizer process traditionally consists of a precipitator, clarification unit, thickener, and mechanical filtration[47]. Recently, this process has been replaced by a solid-liquid fluidized bed in which a crystallization reaction occurs[48]. This technology was first developed as a water softening process. The outlet carbonates from the fluidized bed are in the form of pellets. Thus, the component is commonly referred to as a ‘pellet reactor’.

$$\mathrm{K_2CO_{3(aq)}} + \mathrm{Ca(OH)_{2(s)}} \rightarrow \mathrm{CaCO_{3(s)}} + \mathrm{2KOH_{(aq)}} \qquad \Delta H = -5.8\ kJ/mol \qquad (2)$$

III. Calciner

The calcium carbonate pellets from the pellet reactor are first dried using the slaker (see below) as a preheater and then sent to the calciner, which is a circulating fluidized bed heated to 900 °C[45]. There, the calcium carbonate decomposes into calcium oxide and CO_2, as expressed by Eq. (3). The heat for the calcination process is produced through oxy-firing natural gas, which outputs a CO_2/H_2O mixture as a flue gas that is sent for water removal and CO_2 compression. The use of natural gas results in an increase in the amount of CO_2 that needs to be transported and stored (1.48 tCO_2 per tonne of CO_2 removed from air[49]), and this constitutes one of the main drawbacks of absorption-based DAC. This highlights the importance of electrification and component development for absorption-based technologies.

$$\mathrm{CaCO_{3(s)}} \rightarrow \mathrm{CaO_{(s)}} + \mathrm{CO_{2(g)}} \qquad \Delta H = 178.3\ kJ/mol \qquad (3)$$

IV. Slaker

The slaker is a bubbling fluidized bed in which calcium oxide from the calciner reacts with steam to regenerate calcium hydroxide, as expressed by Eq. (4):

$$\mathrm{CaO_{(s)}} + \mathrm{H_2O_{(l)}} \rightarrow \mathrm{Ca(OH)_{2(s)}} \qquad \Delta H = -63.9\ kJ/mol \qquad (4)$$

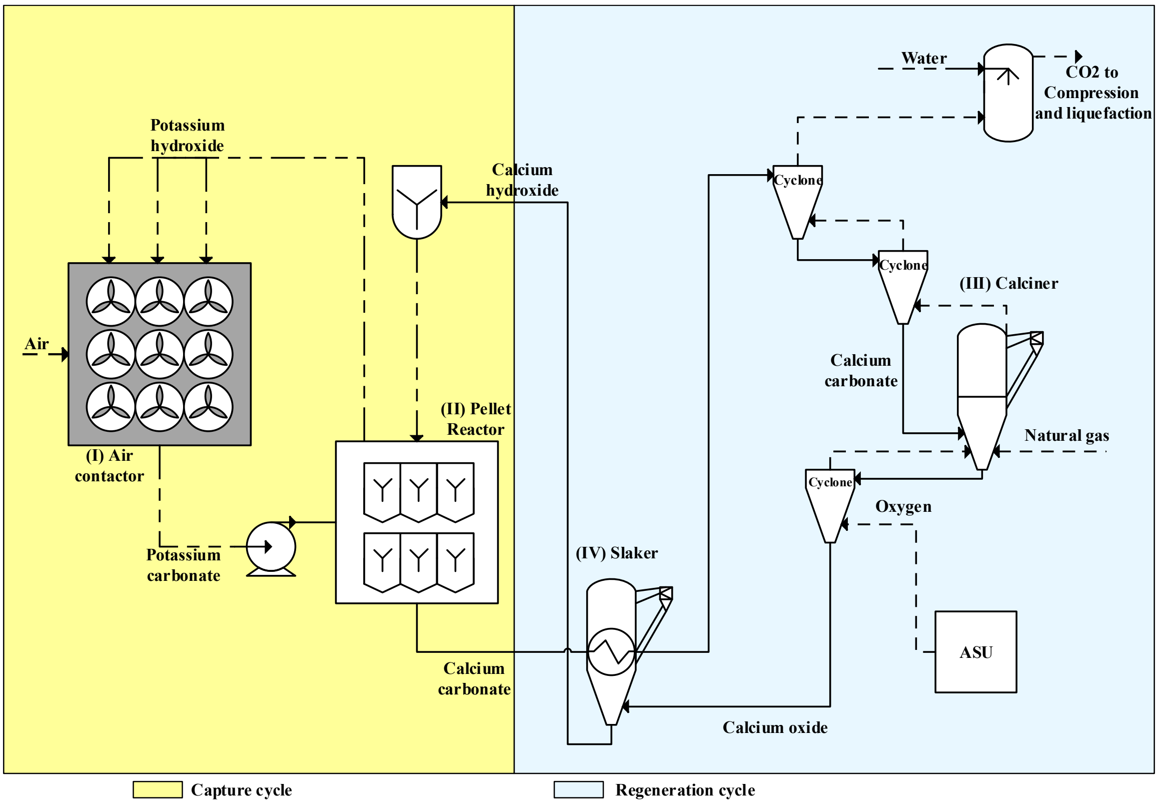


Figure 4: Process scheme for absorption-based DAC.

1.4.2 Adsorption-based DAC

Adsorption-based DAC has received significant attention in the literature, mostly due to the relatively low temperature (around 80 °–120 °C) of the required heat input. This makes it possible to integrate the process at limited scale into industrial processes that have available waste heat[50–52]. The adsorption process works based on the affinities of the sorbent for certain gaseous species under different conditions[53]. For DAC purposes, the sorbents researched are commonly in the solid state, such that the term ‘solid-DAC’ (S-DAC) is a commonly used alternative name.

Adsorption-based processes can be characterized according to:

- Gas-solid contactor design

  The first step of every adsorption process is the actual adsorption step, in which air is brought into contact with the sorbent material. Due to the low concentration of CO_2 in the atmosphere, a large volume of air needs to pass through the sorbent material in order to saturate it. Therefore, designing an air contactor that entails a trade-off between a small pressure drop and a large gas-to-solids surface is essential for reducing the power consumption of the fan/blower. Various contact methods and contactor designs, such as fluidized bed[54], packed bed[55], and monoliths[56,57], have been proposed for DAC applications. However, only the packed bed and monolith design has shown promising results[55,56,58].

- Regeneration method

  The amount of gas adsorbed in an adsorption process is a function of the temperature, pressure, and composition of the inlet stream[59]. Thus, different adsorption processes are identified based on the adsorption and desorption/regeneration conditions. The three main sorbent regeneration methods for DAC purposes are:

  1. Temperature swing adsorption (TSA), in which the sorbent is heated up for desorption.
  2. Steam-assisted temperature swing adsorption, in which the sorbent is forced into contact with steam to increase its temperature and maintain a low partial pressure of CO_2 during desorption. Such steam-assisted desorption results in faster regeneration of the sorbent and larger effective working capacities of the regenerated sorbent. On the other hand, the regenerated sorbent will contain residual water, and the product stream will have a high moisture content, requiring a condensation step[60].
  3. Temperature vacuum swing adsorption (TVSA), in which desorption occurs at a higher temperature and lower pressure than the ambient conditions, by means of a vacuum pump (requiring extra electricity[61,62]) and temperature control. This cycle allows for the utilization of heat at lower temperatures than for TSA.

- Sorbent material

  The main sorbent attributes of interest are internal mass transfer, heat conductivity, and adsorption kinetics[63]. Amine-functionalized sorbents are the most commonly used materials for DAC adsorption processes, mainly due to their adsorption kinetics and performance in the presence of moisture[61]. Their adsorption of CO_2 is enhanced through the adsorption of water, although the level of enhancement declines as the level of water adsorption increases. Adsorption-based DAC generates a stream of water as a byproduct. Climeworks (the commercial technology provider for adsorption-based DAC) reports 0.8–2.0 tH_2O/tCO_2 due to the co-adsorption of water and CO_2 on their sorbent. This would allow co-location of DAC with an electrolyzer and methanation unit for carbon capture and utilization purposes[64].

Unlike absorption processes in which each process step occurs within a dedicated component unit, most of the adsorption processes are modular, with the entire process happening in a single module. Figure 5 shows the six main steps of the TVSA DAC process that has been commercialized by Climeworks[65]. This process uses an amine-functionalized sorbent that is encapsulated in metal frames and arranged in a zigzag pattern inside the contactor frame[55]. The process consists of the following steps:

1. Adsorption: Inlet and outlet are open for air to pass through the reactor, where water and CO_2 are adsorbed, and the CO_2-lean gas is vented.
2. Blow-down: The inlet is closed, and a vacuum pump reduces the pressure to 0.2 bar by venting the gas remaining in the column (waste gas) via a vacuum pump.

3. Preheating: The inlet is closed, and the bed is heated while the vacuum pump maintains the desorption pressure. The desorbed gases (predominantly water at this stage) are vented.
4. Desorption: The inlet is closed, and the bed is heated to the desorption temperature of 100 °C (80 °–120 °C) and the CO_2-rich desorbed gas is collected for further processing.
5. Cooling: The inlet and outlet of the column are closed, and the bed is allowed to cool to 90 °C (to avoid sorbent oxidation)[61] through heat exchange with the ambient air.
6. Pressurization: The inlet of the column is opened, and a new batch of air is allowed to enter the reactor, thereby increasing the pressure to the adsorption pressure level and re-starting the cycle.

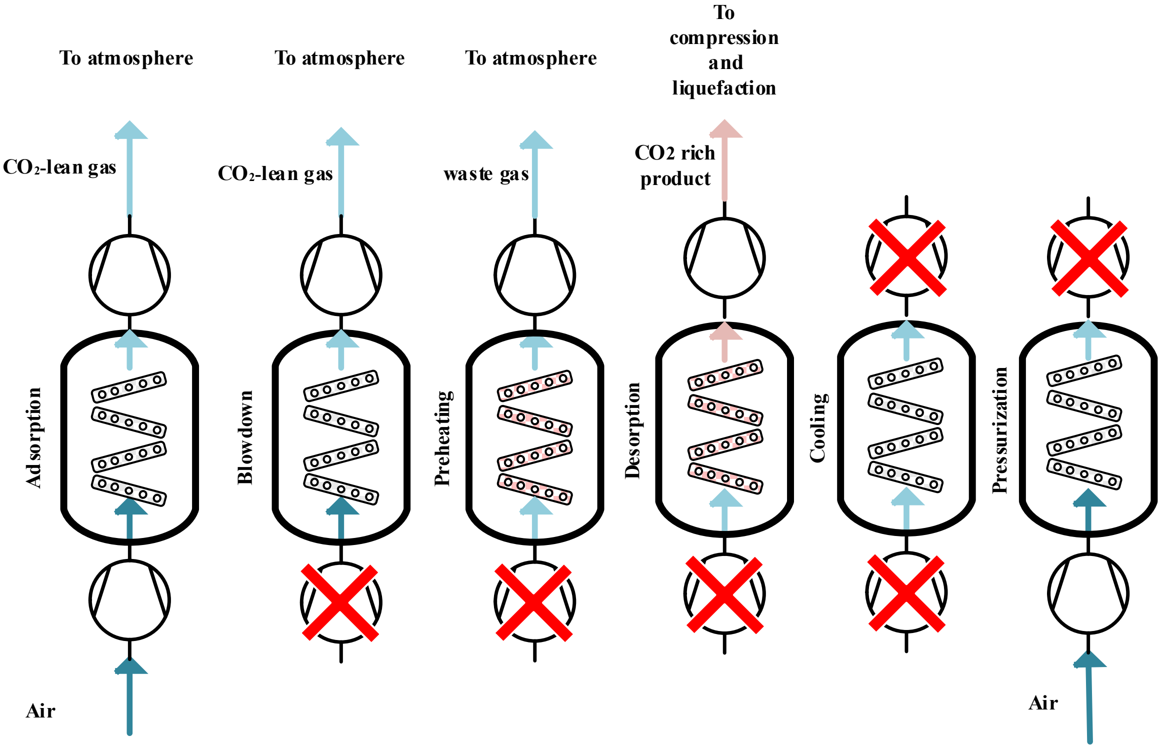


Figure 5: Process steps for the temperature vacuum swing adsorption (TVSA) process.

1.4.3 Ion exchange-based DAC

The ion exchange (also called 'moisture swing') process was introduced by Klaus Lackner in 2009[66]. This process removes CO_2 by bringing open air into contact with a membrane composed of the sorbent, which is a type of anionic exchange resin. The material contains chloride ions, which are replaced by hydroxide and carbonate ions when the material is immersed in solutions that contain these ions. These ions bind to CO_2 in the form of bicarbonate, according to Eq. (5) (dots represent a weak bond between molecules):

$$CO_3^{2-}(R^+)_2.xH_2O + CO_{2(g)} \leftrightarrow 2[HCO_3^- R^+.yH_2O] + (x-2y-1)H_2O_{(g)} \qquad (5)$$

In order to release the CO_2, the equilibrium can be pushed backwards by exposing the saturated material to water vapor. Thereafter, the material is placed back in contact with ambient air for natural drying. The sorbent will cycle between the carbonate and bicarbonate forms. Since each bicarbonate needs one positive charge and each carbonate needs two positive charges, the maximum loading of the material is equal to half of the positive charge concentration.

1.4.4 Electrochemical DAC

Electrochemical processes for the electrification of DAC processes have recently come into focus. Electrodialysis is one of the main electrochemical DAC systems[67]. In this process, hydrogen is sent to an anode to produce ionic hydrogen, while air is sent to a cathode to generate hydroxide. The CO_2 is absorbed by hydroxide at the cathode, yielding carbonate or bicarbonate, which reacts with hydrogen at the anode to release CO_2.

Electro-swing adsorption is another electrochemical DAC process, in which air passes through a nanotube composed of sorbent[68]. The affinity of the specific sorbent in this process for CO_2 can be increased by positively charging the material. When the material is saturated, the process is reversed by changing the polarization to release CO_2.

The main advantage of electrochemical processes is that there is no need for many auxiliary components, such as heat exchangers, or for heating up large volumes of material, and this increases the thermodynamic efficiency of the system. Moreover, in electrochemical processes, unlike adsorption processes, CO_2 is directly targeted and removed without the involvement of any secondary output streams. On the other hand, conveying air through the fuel cell requires high fan power. Electrochemical processes for DAC are still in the early stages of development, and the stabilities of the sorbent materials remain to be proven. Therefore, they are not considered in this work.

1.4.5 Passive Direct Air Capture

Passive DAC generally refers to processes in which the wind naturally moves air through the sorbent instead of the air being moved by a fan, thereby reducing the energy requirement per tCO_2-removed[30,68]. Carbonation of natural hydroxides is the most-intensely studied passive DAC process. Given that natural carbonation is a slow process, passive DAC systems are generally very slow, which means that they require a large area for sorbent distribution. As in the case of absorption-based DAC, once calcium hydroxide is converted to calcium carbonate, it is sent to a calciner[69,70]. Thereafter, the outlet calcium oxide reacts with steam to regenerate the calcium hydroxide. The company Heirloom has commercialized a passive DAC technology that uses calcium hydroxide as the sorbent[71]. Passive DAC processes are not included in this work due to poor availability of relevant data.

1.5 Comparison of the different technologies

Table 2 presents the energy and material requirements of some of the DAC technologies reported in the literature. The technology readiness level (TRL) and cost of capture for each process are shown when available.

Table 2: Energy and material requirements for some of the DAC technologies studied in the literature. Source: **Paper I**.

Technology	**Material**	**Heat [kWh/tCO_2]**	**Electricity, [kWh/tCO_2]**	**Capacity loss/recovery [%/cycle]**	**Material consumption [kg/tCO_2]**	**Cost reported [$/t$CO_2$]**	**TRL**
Adsorption TVS	Amine functionalized[72,73]	1,500–3,305	500–700	0.05[74,75]	13.87	280–580[42]	7–8
	MOF(Cr)[76]	2,688	220	1.5[74]	531.51		3–4
	MOF(Mg)[76]	1,319	201	0.005[74]	0.73		3–4
	PEI on alumina[56]	1,656	218	0.05[74]	7.39		5–6
	K_2CO_3/AL_2O_3[77]	889	945	0.21[77]	75.26		3–4
	Hydrated K_2CO_3[78]	1,170–1,410	150–260	0.05	88.77	220–270[42]	3–4
Adsorption TSA	TRI-PE-MCM-41[79]	2,102	76	6.25[74]	3435		3–4
	PEI on silica[54]	2,083	694	0.05[74]	7.39		3–4
Absorption	KOH (NG + grid)[38,45]	1,458	366	1	25.45 KOH, 30.86 $CaCO_3$	225–545[42]	6–7
	KOH (NG only)[38,45]	2,450	0	1	25.45 KOH, 30.86 $CaCO_3$		6–7
	NaOH[47]	1,678	440	1	18.18 NaOH, 228 $CaCO_3$[47,80]		
	NaOH[81]	2,250	494	1	18.18 NaOH, 3.5 $CaCO_3$ [47,80,82]		
Ion exchange	Anionic exchange resin[66,83,84]	0	378	Max 100,000 cycles[85]	1.515–2.02[85]	110[42]	3–5

MOF, metal-organic framework; TRI-PE-MCM, Triamine-grafted pore-expanded mesoporous silica; PEI, polyethylenimine; NG, natural gas.

To compare the DAC technologies with respect to their usage levels of materials, electricity, and heat, the efficiency of each DAC technology has been calculated from three perspectives.

First-law perspective: Provides an overview of the total energy demand per tCO_2-captured.

$$\eta_I = \frac{W_{min,CO2}}{EL_{in} + Q_{in}} \tag{6}$$

Second-law perspective: Takes into account the equivalent work value of the heat supplied by considering its relative temperature level.

$$\eta_{II} = \frac{W_{min,CO2}}{EL_{in} + Q_{in} * \left(1 - \frac{\mathrm{T_{env}}}{\mathrm{T_{bf}}}\right)} \tag{7}$$

Exergy perspective: As illustrated in Figure 3, DAC uses heat, electricity, and fresh chemical materials to remove CO_2 from the atmosphere. While the second-law perspective includes electricity and the work equivalent value of heat, it neglects the material flows. The exergy perspective takes into consideration the work equivalent value of the material flows through their chemical exergy, thereby accounting for the impact of material degradation and the thermodynamic value of the chemical material.

$$\eta_{ex} = \frac{Ex_{ch,CO_2}}{\sum Ex_{ch,in} - \sum Ex_{ch,byproducts}} \tag{8}$$

Figure 6 shows the values of these three efficiencies for the DAC processes considered (see Table 2). The ion exchange process presents a very high (32.3%) first-law efficiency [Eq. (6)] relative to the others, due to recovery with moisture at very low temperatures. For all the other processes, the first-law efficiency is <10%, due to the low concentration of CO_2 in the atmosphere. The efficiency based on the second-law perspective [Eq. (7)] shows higher values for all technologies, with the exception of absorption-based DAC. This highlights a drawback of high-temperature processes.

Finally, the exergy-based efficiency, as expressed by Eq. (8), drops for all processes due to the consideration of chemical degradation of the material.

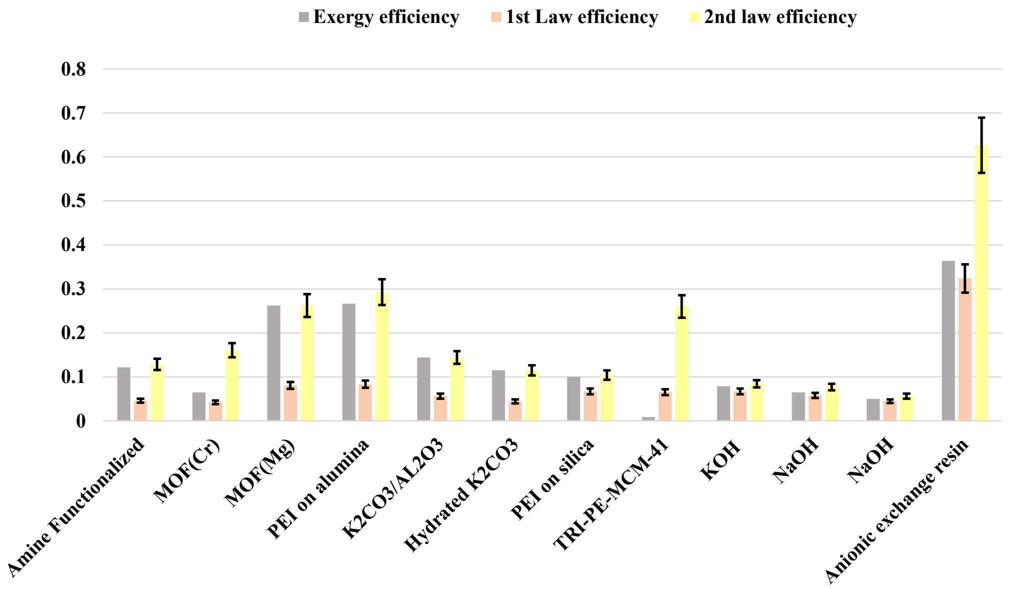


Figure 6: Efficiency values of the different DAC systems, based on first-law [Eq. (6)], second-law [Eq. (7)], and exergy [Eq. (8)] perspectives. The black bars indicate the value ranges based on available data from the literature. Source: **Paper I.**

Figure 7 shows the breakdown of the exergy demand and OPEX for the two most-commercialized DAC technologies. The exergy results (Figure 7a) show the range of the share of chemical exergy in the total exergy demand, based on a sensitivity analysis of material degradation rates. Low and high rates of degradation correspond to 50% lower and 100% higher values than the baseline values reported in the literature, respectively[74,75,86]. As shown, the share of the exergy demand related to material consumption (chemical exergy) is large (around 50%) for TVSA and relatively small (≤10%) for ALK-ABS, with degradation playing a relatively minor role. This is reflected in the material-related OPEX as shares of roughly 20% and 10%, respectively, due to a relatively low cost for material compared to the costs for heat and electricity. Overall, the results highlight the greater importance of sorbent properties (cost, performance, degradation) for TVSA compared to ALK-ABS.

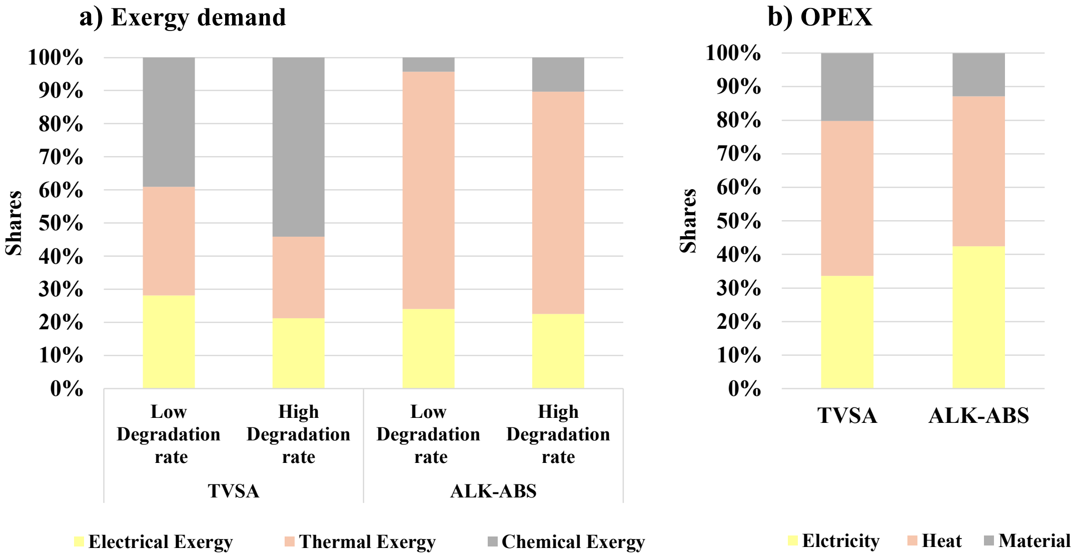


Figure 7: Breakdown of the exergy demands and OPEX across the electricity, heat, and material flows.

Methodology

This chapter briefly presents the overall methodology used in this thesis to address the three research questions. For more detailed descriptions of the methodologies, the reader is directed to the appended papers.

Aligning with the common practice of using cost metrics as the primary decision-making criterion, the assessment framework used in this thesis is based on comparing net carbon removal costs, carbon avoidance cost (CAC), and the current willingness to pay in the form of current prices in voluntary carbon offset markets (here referred to as 'CDR credit prices'). A techno-economic model is employed to estimate the net carbon removal costs and CAC, based on flow and size data derived from energy and mass balances, which are closed through models at the process or plant level.

As shown schematically in Figure 8, the framework utilized in this work evaluates the deployment opportunities for DAC identified in this thesis. These deployment opportunities are categorized into three types: direct implementation, alternative application, and financing opportunities.

When considering the opportunities related to the deployment of DAC, the cost of implementing a DAC-derived solution must be lower than the market price of carbon removal credits for the application to be economically viable. It should be noted that there are currently no official markets for CDR credits, and the prices considered here are based on information obtained from the websites of major DAC technology providers and their future CDR credit sales[87–89]. Under such conditions, DAC deployment can be justified as a profitable source of carbon removal credits. In this thesis, a deployment opportunity has been investigated within the framework of **RQ I**.

Alternative application opportunities arise when DAC-derived technologies can be applied beyond conventional carbon removal. Such opportunities exist when a new DAC-derived application achieves CACs that are lower than both the net removal cost of DAC and the CAC or marginal CAC of the benchmark CCS. This comparison reflects a medium- to long-term perspective, in which DAC is assumed to be deployed at larger scales and its costs are expected to decline. From this standpoint, alternative applications of DAC technologies may offer more cost-effective mitigation pathways, so they are particularly relevant for medium to long-term ,here referring to the time period beyond reaching 1mtpa cumulative deployed capacity for each technology, emissions mitigation. In this thesis, two such alternative application opportunities are investigated within **RQ II** and **RQ III**.

Finally, financing opportunities are defined from the perspective of the short-term, here referring to the time period before reaching 1mtpa cumulative deployed capacity for each technology, mitigation demand for carbon removal credits, where relative CACs become the determining factor. When these avoidance costs are compared with CDR credit prices, the analysis reflects short-term abatement strategies, as the current prices in voluntary carbon markets do not fully represent the actual costs of DAC. If the price of carbon removal credits is lower than the CAC, purchasing such credits may be a more economically advantageous alternative to onsite capture in the near term. At the same time, this demand can support early DAC deployment and contribute to future cost reductions, thereby creating a pathway to finance offsets via DAC. In this thesis, such financing opportunities for DAC are investigated within **RQ II** and **RQ III**.

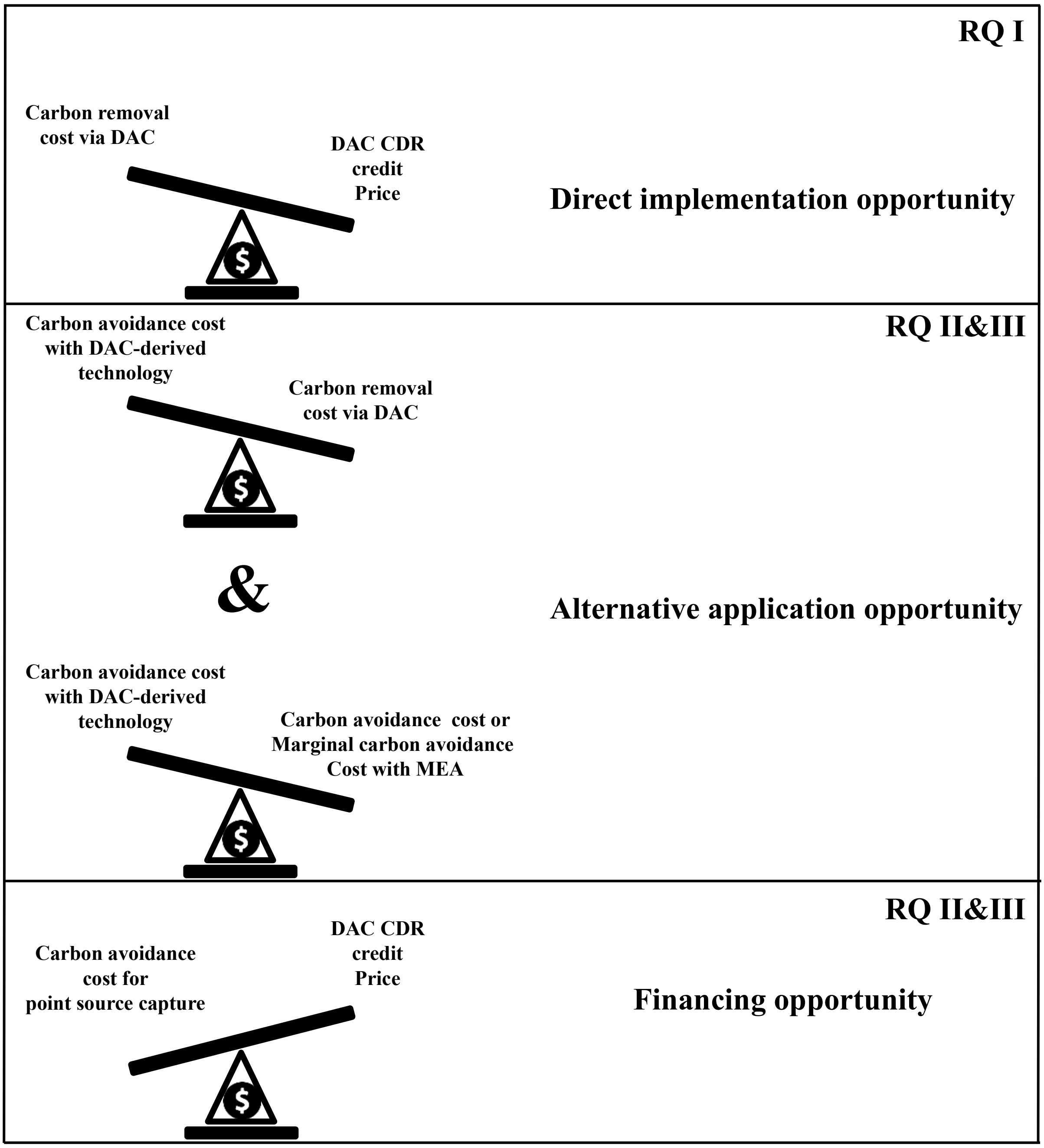


Figure 8: Framework for identifying DAC opportunities related to: 1) direct implementation; 2) Alternative application; and 3) financing.

Figure 9 shows the assessment framework of this thesis with the models used to address each research question. For **RQ I (**investigated in **Paper II)**, the plant model represents an optimization framework that integrates the process model, the techno-economic assessment, and the comparison with CDR credit prices. In contrast, for **RQ II** and **RQ III** (investigated in **Papers III** and **IV**), a process model is used to close the heat and mass balances and thereby determine the sizing of the components. Thereafter, a techno-economic model uses these results to assess the carbon removal/avoidance costs, which are compared with the CDR credit prices to assess economic viability. The following sections provide summaries for each of the models used.

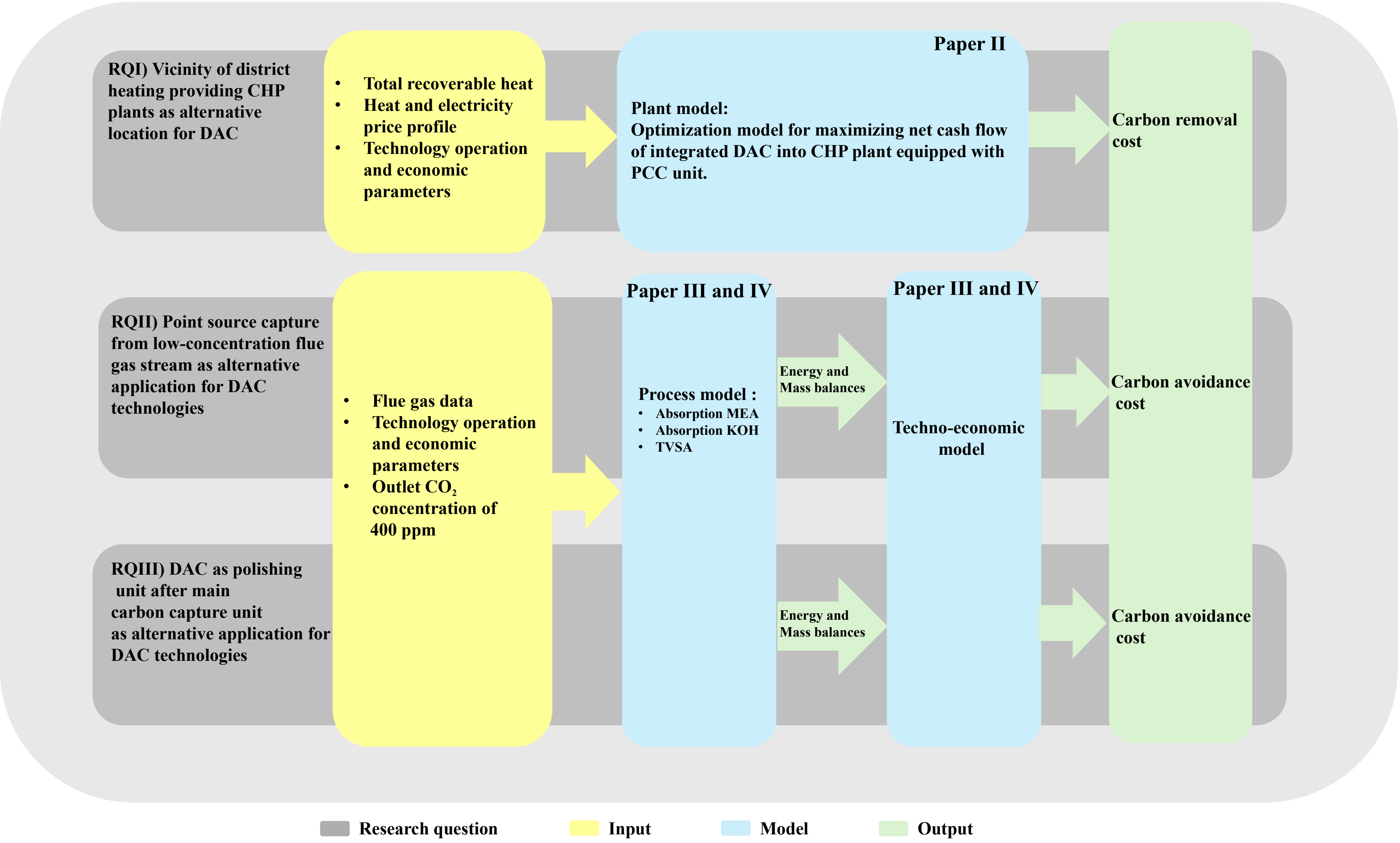


Figure 9: Graphical representation of the assessment framework used in this thesis.

1.6 Process modeling

The process models used to close the mass and energy balances are summarized below. Based on the results from these models, the equipment for each process was sized to achieve either an outlet CO_2 concentration of 400 ppm in a single carbon capture step (**Papers III** and **IV**) or net-zero direct CO_2 emissions via multiple carbon capture steps (**Paper IV**).

- Absorption via KOH (ALK-ABS)

  A steady-state process model for absorption via KOH with subsequent calcium looping was developed in Aspen Plus v14.0. The model follows the general description given by Keith et al.[45], albeit using electricity from the grid instead of from a dedicated power island. The air contactor component is modeled using a rate-based model built-in absorption column in Aspen Plus, and is sized by varying the gas flow rate to achieve the desired capture rate. The remainder of the components and flows are also sized to maintain a calcination temperature of 900 °C in the calciner. Here, a 90% retention rate in the pellet reactor and a 30 wt% concentration of calcium hydroxide after the slaker are considered based on the descriptions in the literature [9,45,48,90,91].

- Temperature vacuum swing adsorption (TVSA)

  A 1-D transient model of a six-step cycle in a TVSA column was developed in gPROMS using its built-in adsorption column model. When moving from atmospheric concentrations towards higher concentrations of CO_2, the thickness of the zigzag plates in the DAC design is allowed to increase by stacking several plates. This allows longer gas residence times in the unit. When the thickness of a stack exceeds 1.5 m, the column completely transitions towards a classical adsorption column design. Customized codes for adsorption isotherms[61] and a co-adsorption model were added to account for the enhancement of CO_2 adsorption through co-adsorption of water[61]. The model was run in a Monte Carlo analysis framework (varying the times of adsorption, heating, and desorption, as well as column height and inlet water content), with the result of each run being subsequently used as input to the techno-economic model[92], in order to identify the configuration and operation with the lowest cost.

- Absorption via MEA (MEA)

  This technique, used as the benchmark for point-source carbon capture, is described through two steady-state process models constructed in Aspen Plus v14.0 and Aspen HYSYS V14.0. These models include downstream compression and liquefaction. The MEA model used in **Paper III** is based on the work of Biermann et al.[93], while the MEA model used in **Paper IV** is based on the work of Subraveti et al.[94]. The compression and liquefaction model is based on the work of Deng et al.[95], and is dimensioned so that the outlet CO_2 stream composition meets the specifications for medium-pressure ship transport established in the Northern Lights project[96].

1.6.1 Material choice and degradation

Material degradation can be a major contributor to both the cost and environmental performance of DAC depending on material cost and characteristics. This thesis uses fixed sorbent and solvent specifications for each of the capture technologies considered.

For ALK-ABS, only two solvents are currently known, KOH and NAOH, of which only KOH has been used for commercial application. Material degradation profiles for ALK-ABS have been considered using data from the pulp and paper industry for KOH[97] and data from Keith et al.[45] for $CaCO_3$

For TVSA, a wide range of sorbent materials is available, each with the potential to improve or worsen system performance. This thesis uses 'Lewatit VP OC 1065' [98], which is the material with the most-comprehensive data available in the literature, for **Papers III** and **IV**, and amine on cellulose for **Paper II**, based on reported industrial values in the literature[73]. This thesis applies a constant degradation rate of 7.5 kg/t CO_2 for TVSA as derived from industrial data, though this value may differ under point source capture conditions.

MEA scrubbing with 30 wt% MEA is used as the benchmark carbon capture technology in **Papers II**, **III**, and **IV**, and a constant solvent degradation rate per unit of CO_2 captured is applied[94].

1.7 Techno-economic modeling

Figure 10 shows the boundaries used for the cost of capture (COC) [Eq. (9)] and CAC [Eq. (10)].

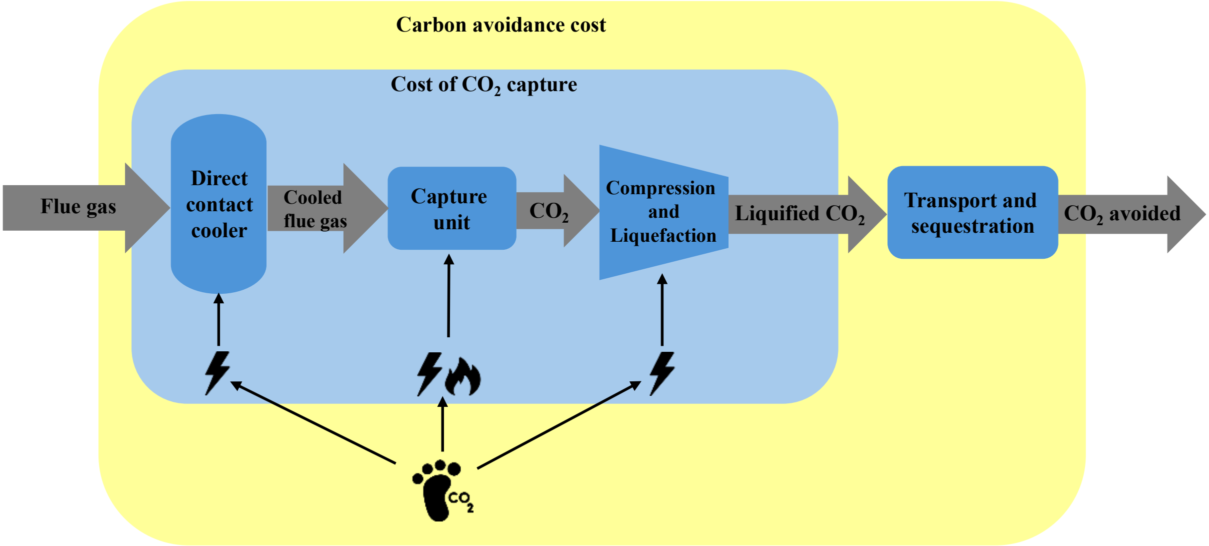


Figure 10: System boundaries for calculating the cost of CO_2 capture (blue frame) and the carbon avoidance cost (yellow frame). Source: **Paper III**.

The COC [Eq. (9)] is used to compare the performance of carbon capture processes, while the CAC [Eq. (10)] includes the transportation and storage costs, to enable comparison of a given process with the net removal costs or CDR credit price. It should be noted that net removal costs (typically used for capture from atmospheric air) and the CAC (typically used for point-source capture) represent the same cost concept.

$$\text{cost of capture} = \frac{C_{\text{inv}} + C_{\text{fixed O\&M}} + C_{\text{variable O\&M}}}{m_{CO_2,\text{captured}}} \tag{9}$$

$$\text{carbon avoidance cost} = \frac{C_{\text{inv}} + C_{\text{fixed O\&M}} + C_{\text{variable O\&M}} + C_{\text{transportation \& storage}}}{m_{CO_2,\text{avoided}}} \tag{10}$$

where $m_{CO2,\ avoided}$ is defined as:

$$m_{CO_2,avoided} = m_{CO_2,captured} - m_{CO_2,electricity} - m_{CO_2,heat} - m_{CO_2,chemicals} \tag{12}$$

The marginal CAC is defined as the additional cost that is required to avoid one additional mass unit of carbon emissions. It is calculated based on the CAC and according to [Eq. (13)], where CR represents the capture rate.

$$\text{Marginal carbon avoidance cost}|_{CR2} = \left.\frac{\partial \text{CAC}}{\partial \text{CR}}\right|_{CR2} = \frac{\text{CAC}\,|_{CR2} - \text{CAC}\,|_{CR1}}{\text{CR2} - \text{CR1}} \quad \text{where CR2} > \text{CR1} \tag{13}$$

The capital investment (C_{inv}) of each component is determined using the bottom-up/top-down cost estimation method shown in Figure 11. The Nth-of-a-kind MEA as high TRL technology lower contingency values consistent with Nth-of-a-kind are used. In case of DAC and DAC-derived technologies, individual learning rates are applied to each component cost and contingency cost, based on the cumulative deployed capacity of the technology to achieve Nth-of-a-kind costs. In this work, a cumulative deployment capacity of 1 Mtpa is considered for future (Nth-of-a-kind) cost estimations. The economic parameters, assumptions, and cost escalation factors are selected based on the case studies. The top-down approach includes extracting data from literature or using vendor data for a whole unit (including all associated equipment), which are typically reported as engineering procurement and construction costs. This approach is used for equipment that is either commercially available or for which data are available in the literature for entire subsystems (e.g., for most of the absorption-based DAC components). The bottom-up approach uses energy and material flow data from the developed process models to size and assess the cost of each piece of equipment. The direct cost of each piece of equipment was obtained from the direct cost data or regressed direct cost functions available in the literature[69,92,99–101] (e.g., for MEA-absorption and TVSA). The total capital requirement (TCR) estimated from the hybrid top-down/bottom-up capital cost estimation method is annualized over the assumed plant lifetime or the design lifetime of the process technology. The fixed operation and maintenance ($C_{fixed,O\&M}$) cost is estimated based on the total plant cost and labor cost required, adopting the previously reported method[100]. The variable operation and maintenance cost, $C_{variable,O\&M}$, is dominated by the costs of electricity and heat, which in this work are based on assumed values. The cost for transportation and storage ($C_{T\&S}$) costs vary substantially according to location and are, therefore, used as a sensitivity parameter in our work for First-of-a-kind, while 50 $/tCO$_2$ is considered for Nth-of-a-kind cost estimations.

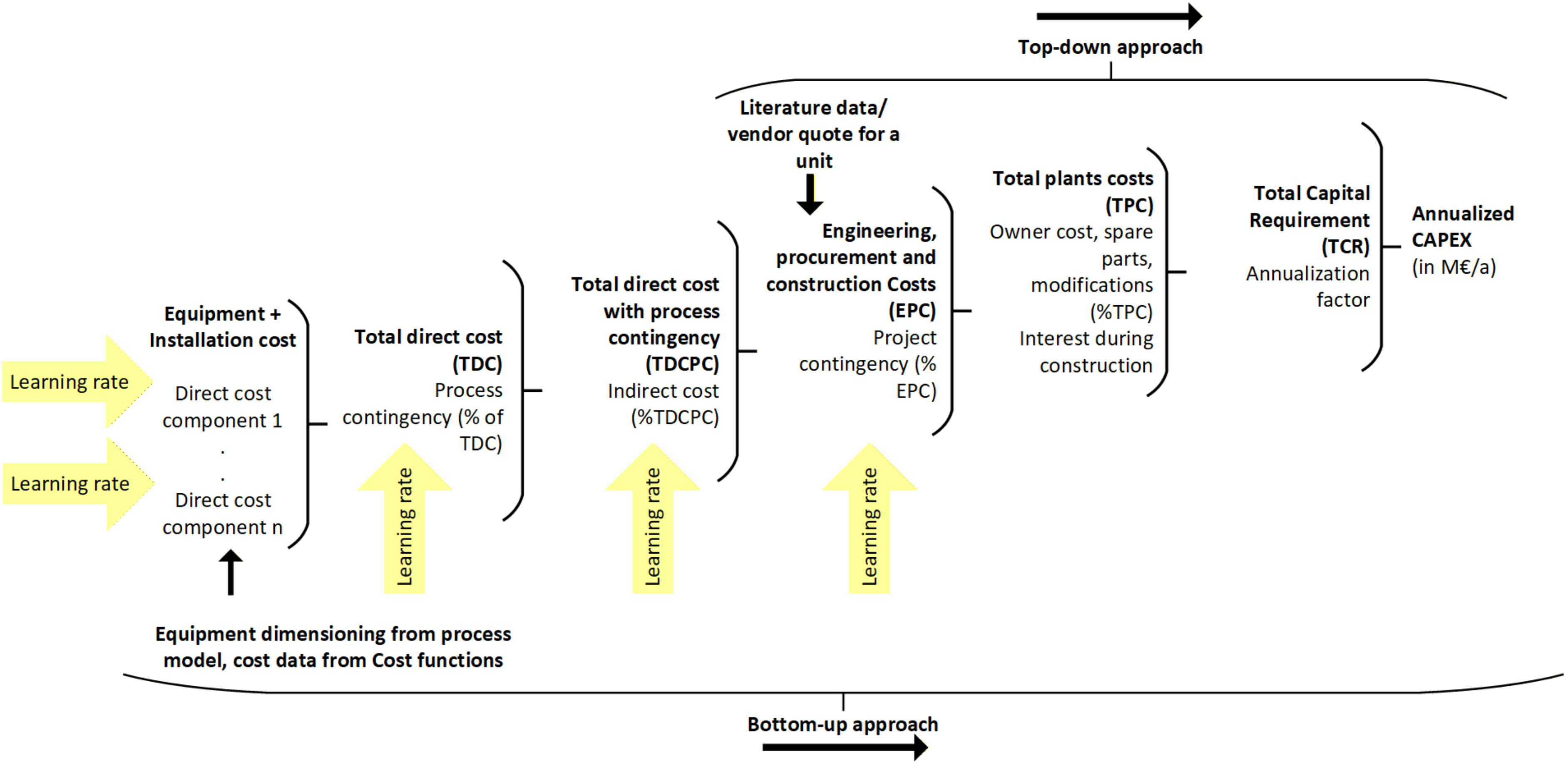


Figure 11: Capital cost estimation method[95,99,102,103]. The vertical black arrows show the entry points of components/unit costs. The horizontal black arrows indicate the directions of the cost scaling factors. The yellow arrows indicate the application points of the learning rates when transitioning from First-of-a-kind to Nth-of-a-kind[41].

1.8 Plant model

A plant model (detailed in **Paper II)** using linear optimization is employed to uncover the optimal integration of DAC with a CHP plant equipped with a post-combustion capture (PCC) unit. Figure 12 shows the overall framework for the investigation of **RQ I** where this plant model is included.

The investigation begins with running an existing process model for a CHP plant with PCC and using the outcome to create the actual cooling load curve, which provides the recoverable heat available at low-temperature (30 °–50 °C) and medium- temperature (50 °–90 °C) levels.

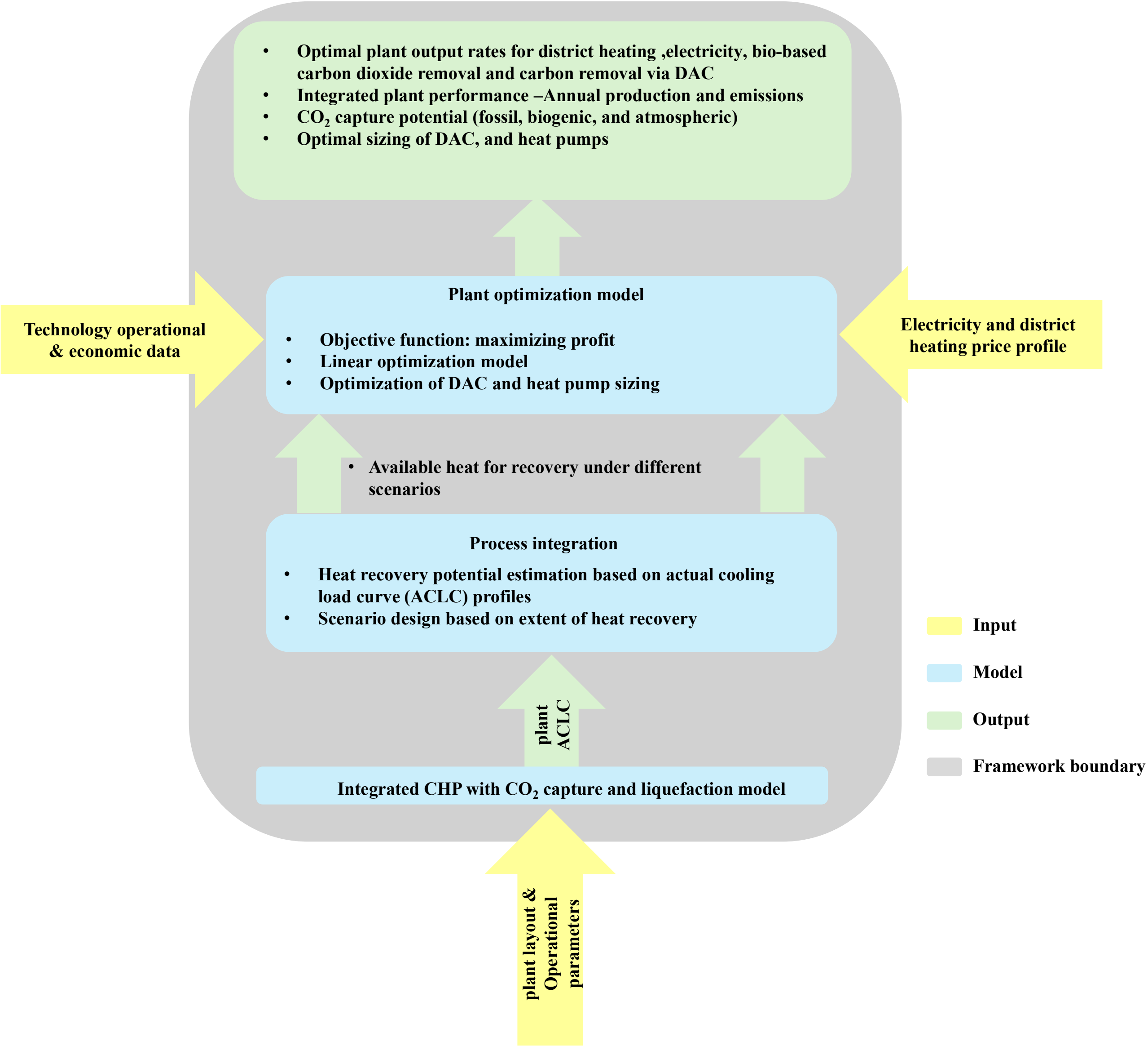


Figure 12: Overall framework for assessing the integration of DAC into CHP plants (**RQ I**). Source: **Paper II.**

A linear optimization framework is then applied to assess the interactions between CHP, DAC, PCC, and the district heating network. This model incorporates the technological and operational parameters of each component, along with heat and electricity price curves. The model sets as an objective the maximization of the plant's annual net cash flow while maintaining the energy and mass balances within the system. For this purpose, the model is allowed to adjust the sizing of the DAC process and operation of the system (dispatch strategy for heat, electricity, and CDR). The net cash flow includes revenues from electricity and district heating sales, CDR credits (from capturing both biogenic and atmospheric CO_2), and avoided CO_2 taxes (from capturing the fossil carbon share of the fuel). On the cost side, fuel and investments in new equipment are considered.

Furthermore, a sensitivity analysis is conducted to study the impacts of five main parameters (heat price, electricity price, electricity price volatility, operational hours, fuel type) on the optimal amount of CDR via DAC. Table 3 presents the values of these parameters for the base case, as well as for a sensitivity analysis.

Table 3: Base case and sensitivity analysis parameters.

	Base case	**Sensitivity analysis**
Heat price	Profile in southern Sweden (SE3) (average, 10.26 €/MWh)	-50%, +50%, +100%, +900%
Electricity price value	Profile in southern Sweden (SE3) in Year 2022 (average, 129 €/MWh)	±30%
Electricity price volatility	Profile in southern Sweden (SE3) in Year 2022	Low: predicted electricity price profile in Year 2050 in northern Sweden (SE1)[104] High: predicted electricity price profile in Year 2050 in southern Sweden (SE4)[104]
Fuel type	Municipal solid waste	Biomass
Operational hours /heat profile	Waste-fired CHP 8,000 full-load hours/year	Bio-CHP plant 4,500 full-load hours/year

1.9 Methodological limitations

The methods presented have several limitations that should be acknowledged before discussing the results.

First, all the assessment frameworks exclude emissions associated with plant construction and end-of-life stages, as these are considered to be negligible relative to the operational emissions, as shown in previous lifecycle assessment (LCA) studies[73,105,106].

Second, constant value of sorbent consumption per ton of CO_2 captured/removed is considered for TVSA process. This value can be affected via change of application due to different cycle times and different saturation levels. A more descriptive, degradation model will be required to gauge this effect.

Third, the plant optimization case (**RQ I**, **Paper II**) considers only the investment costs of the added components and the fuel costs of the plant. Thus, it neglects the investment and other operational costs of the CHP plant. While these costs may influence the investment decision regarding the adoption of the proposed scheme, they are highly case-specific and information on them is often not publicly available. For case-specific applications, including the operational costs could provide a more comprehensive basis for decision-making.

Finally, the pathway comparisons in **RQ II** and **RQ III** (**Papers III** and **IV**) focus exclusively on pathways that involve exclusively carbon capture to achieve net-zero direct emissions, and they do not consider alternative mitigation options, such as electrification or fuel switching.

Results

This chapter presents the main results from **Papers II**, **III** and **IV** in three sections.

Section 4.1 covers the integration of sorbent-based direct air capture (S-DAC) into combined heat and power (CHP) plants equipped with post-combustion carbon capture (**RQ I**, **Paper II**).

Section 4.2 presents the techno-economic performances of DAC-derived technologies applied as point source capture to CO_2-lean industrial flue gases (**RQ II**, **Paper III**).

Section 4.3 examines the complementary roles of DAC and DAC-derived technologies to MEA scrubbing in achieving net-zero direct emissions from CO_2-rich industrial sources (**RQ III**, **Paper IV**).

For each section, the findings with the highest levels of novelty are presented in detail and discussed briefly, while the remaining results are summarized.

1.10 Integration of DAC into combined heat and power plants

The results presented in this section address RQ I and are obtained from the plant model described in Section 3.3. This section assesses a direct implementation opportunity under which DAC integration into CHP plants is directly economically viable as a source of CDR credits, as evaluated for the reference case of a 167 MW_{th} waste-fired CHP plant.

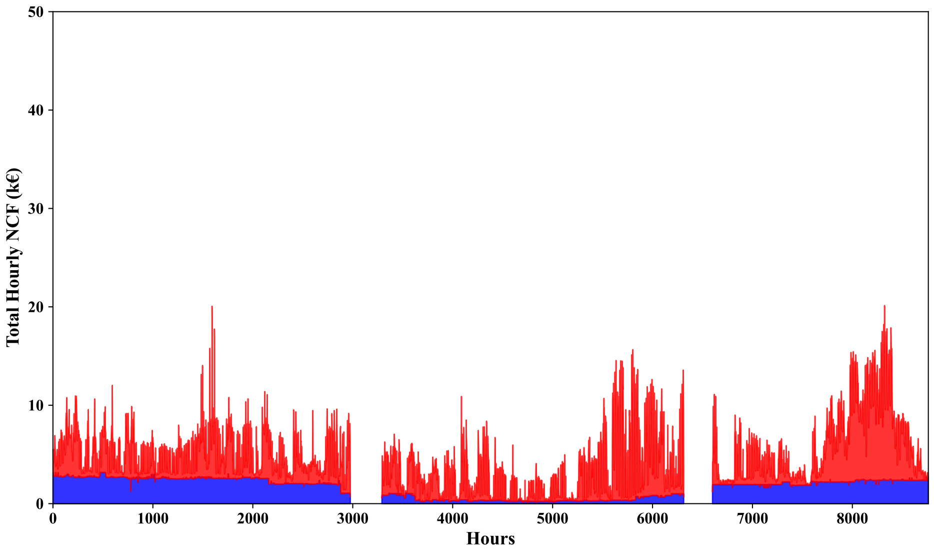
1.10.1 Maximum carbon removal potential and break-even CDR credit prices

The reference plant attains through the addition of PCC a biogenic CDR of 162.7 $ktCO_2/y$. When the added S-DAC unit is sized for maximum carbon removal rather than maximum NCF, i.e., disregarding the economics, the atmospheric CDR potential of the integrated system ranges from 74.8 $ktCO_2/y$ (without any heat recovery from the PCC unit) to more than double that figure, at 158.1 $ktCO_2/y$ (with full heat recovery, but at the cost of requiring larger, low-temperature heat pump installations).

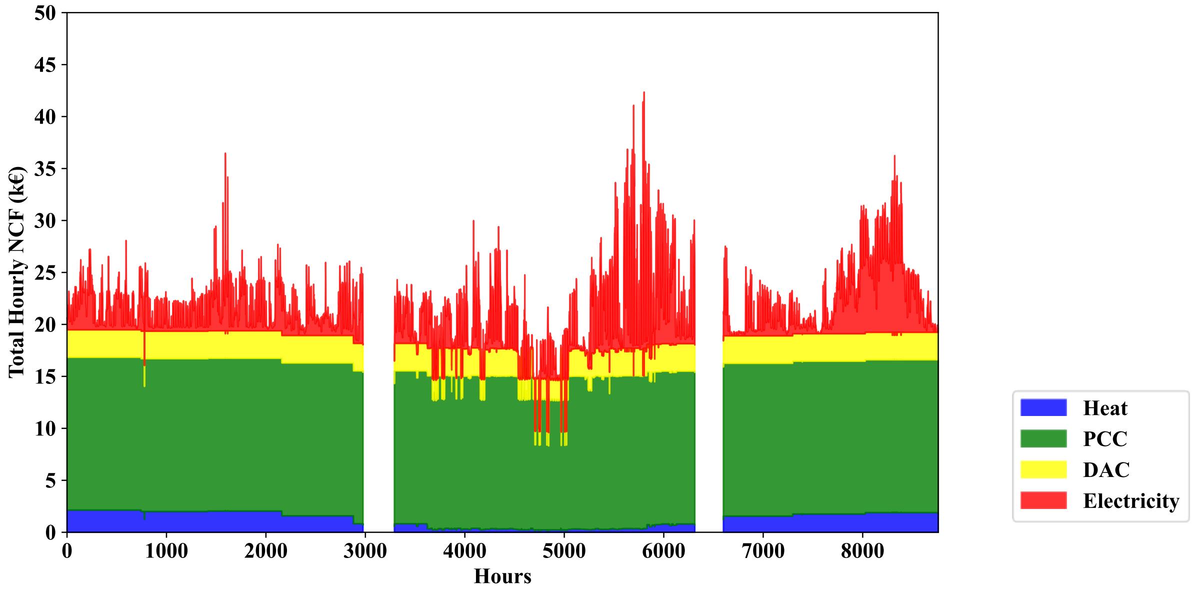
The break-even CDR credit price (the price making the retrofit economically neutral) ranges from 279 €/tCO_2 to 685 €/tCO_2, depending on the retrofit configuration and heat recovery scenario. Crucially, retrofitting a CHP that is not originally equipped with PCC (a so-called 'joint retrofit') yields substantially lower break-even prices (279–405 €/tCO_2) than retrofitting a CHP-PCC plant (620–685 €/tCO_2). This difference arises because in the joint retrofit case, the revenues from biogenic CDR via PCC (which are higher than those accrued via DAC) are credited to the same investment, improving the overall economics of the project.

1.10.2 Economically optimized operation

Figure 13 shows the hourly NCF of the reference CHP plant for both the business-as-usual case (Figure 13a) and the case involving retrofit after the addition of PCC and DAC (Figure 13b). As illustrated in Figure 13a, electricity sales constitute the largest share (68.3%) of the NCF for the assumed business-as-usual conditions (which include an electricity price curve that averages 129 €/MWh).



a) Business as usual



b) Integrated system

Figure 13: Hourly net cash flow (NCF) levels from sales of heat, electricity, CDR via DAC and CO_2 captured from the flue gas, for: a) a business-as-usual scenario (the reference CHP plant before PCC and DAC integration) and b) a CHP plant after PCC and DAC integration. Note that the two time periods without production correspond to maintenance shutdowns. Source: **Paper II**.

According to Figure 13b, for a CDR credit selling price of 615 €/tCO_2 (assumed based on the DAC cost estimation from[41] and 65 €/tCO_2 for transportation and storage), the integration of PCC and DAC yields a large increase in the NCF, entailing contributions from DAC (11.8%), the capture of biogenic CO_2 via PCC (67.1%), electricity sales (14.9%), and heat sales (6%). Furthermore, the retrofit implies a reduction in the plant's net outputs of heat (13%) and electricity (37%), which might be problematic in smaller energy systems that have little redundancy. The results show that entering the CDR market at the estimated CDR credit price offers a profitable business case for CHP plants in which CDR becomes the plant's main product. Such an increase in NCF can prolong the operation of CHP plants, thereby allowing extended use of the available infrastructure before the transition to a electrified heating system. Furthermore, CDR through the capture of biogenic CO_2 raises concerns regarding the efficient use of biomass, which needs to be addressed at the policy level.

The optimization results for the base case indicate that a total of 237 $kgCO_2$ per MWh of fuel combusted can be removed from the atmosphere, with DAC accounting for 82 kg/MWh_{fuel}. At a CDR credit price of 615 €/tCO_2, this corresponds to a NCF value of 145 €/MWh_{fuel} (with DAC contributing 54.4 €/MWh_{fuel}), as compared with 5 €/MWh_{fuel} for heat and 55.8 €/MWh_{fuel} for electricity. This positions CDR as the most-profitable product from the NCF perspective. Given full operational flexibility, the plant would, therefore, prioritize operation for CDR.

In Nordic countries, where a high number of CHP plants deliver heat for district heating, grid-wide implementation of such a system could contribute a large share of the CDR demand to enable the country to reach its climate target. In Sweden, for example, 82 $kgCO_2/MWh_{fuel}$ would result in 3.3 Mt of CDR via DAC if this system was implemented in all CHP plants with thermal capacities >50 MW.

1.10.3 Sensitivity analysis

Figure 14 shows the results of the sensitivity analysis for different parameters (fuel type, operational hours, electricity price volatility, electricity price, heat price — see Table 3) with respect to the total CDR achieved by the integrated system. According to the results, the total CDR achieved by the PCC unit only varies for those parameters that change the total amount of biogenic CO_2 generated by the plant (i.e., operational hours and fuel type), since the model is constrained to capture 90% of the CO_2 emissions. The total CDR achieved via DAC instead responds positively to heat availability and reacts negatively to electricity and heat prices. This can be interpreted as the integration of DAC to CHP plants being a less-favorable choice for demand-following plants as compared with base-load plants. The electricity price presents a stronger impact on the total cost of CDR via DAC than the heat price, mainly due to the fact that the electricity prices used here are much higher than the heat prices. Electricity price volatility does not appear to influence significantly the results.

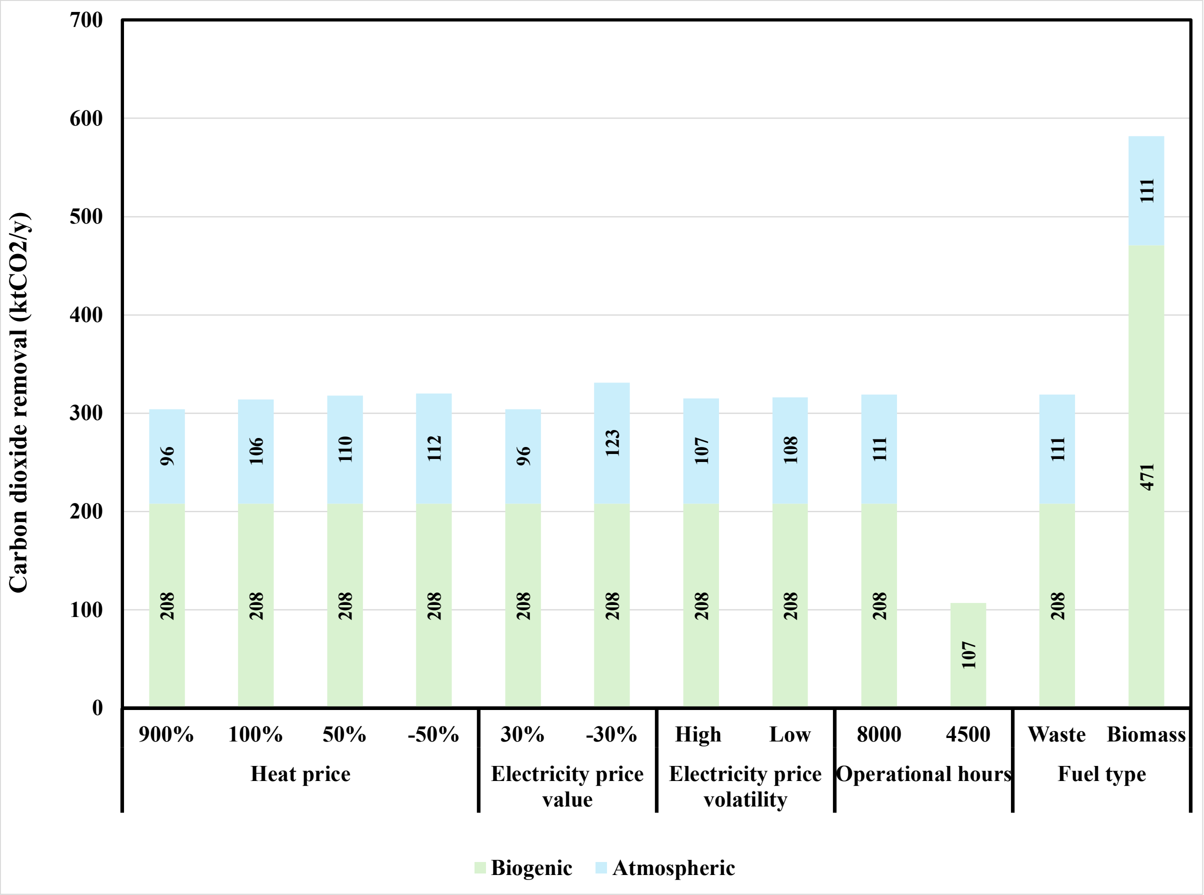


Figure 14: Sensitivity of the level of carbon dioxide removal (CDR) to five key parameters for the CHP-PCC-DAC system. Source: **Paper II**.

The total operational hours of the plant have a strong impact, as DAC is a capital-intensive technology and, thus, requires high-capacity usage to become cost-competitive. Therefore, in the case of low numbers of operational hours, the optimal strategy is to avoid deployment of the DAC retrofit (i.e., the optimized DAC capacity resulting from the model is equal to zero).

The fuel shift (biomass and waste are considered) does not show any substantial impact on the total CDR via DAC, since they both make the same amount of heat available for DAC.

As discussed above, DAC is and will continue to be a capital-intensive technology. Therefore, the combination of DAC capital costs and CDR credit prices represents a key determinant of the economic feasibility of such integration. Given the uncertainty related to future DAC costs and CDR credit prices, such feasibility is evaluated in terms of the minimum CDR credit price at which the integrated system would become economically viable. To this end, two scenarios are explored: an optimistic case with a specific investment cost of 8 M€/(tCO_2·h) installed capacity; and a higher-cost case of 70 M€/(tCO_2·h) installed capacity based on the projected levelized capital cost of DAC[69]. The results show that, for an investment cost of 8 M€/tCO_2, S-DAC appears in the optimal solution at a CDR credit price of 215 €/tCO_2. In contrast, for an investment cost of 70 M€/(tCO_2·h), the corresponding threshold increases to 940 €/tCO_2.

The techno-economic assessment results indicate that the integration into CHP plants represent a promising opportunity for the deployment of DAC from an economic perspective. However, the feasibility of this integrated system depends on the deployment of CCS, which in turn requires access to transport and storage infrastructure. Therefore, in the short term, such systems are best suited to district heating plants located near ports, where CO_2 can be transported by ship. In the long term, as the transport and storage infrastructure expands, the integrated system could be applied to any district heating system with CHP plants.

1.10.4 Environmental trade-off

One aspect to consider is that, in general, the low-grade heat (at approximately 100 °C) required to operate the DAC unit could have alternative uses. Here, from a general perspective, the environmental benefit of using low-grade heat for DAC is compared to two alternative uses: for district heating (thereby displacing heat assumed to be supplied by heat pumps) or for electricity generation via an organic Rankine cycle (ORC). Figure 15 illustrates the environmental trade-offs that occur when using 1 MWh of 100 °C heat for these different technologies as a function of the carbon intensity of electricity[107]. The solid and dashed lines represent the least (current performance) and most (envisioned performance) favorable technology performance levels. The vertical lines represent the average carbon intensities of electricity generated via specific technologies or for different countries. The data used to generate this figure is provided in Table 2 in the *Appendix.*

As seen in Figure 15, as the carbon intensity of electricity increases the net CO_2 removed via DAC decreases due to the higher indirect emissions associated with its electricity consumption. In contrast, the amount of CO_2 avoided through using the heat for district heating or for ORC electricity generation increases with carbon intensity of electricity, as these options displace more carbon-intensive marginal energy sources. According to Figure 15, for most European countries, the use of 100 °C heat for DAC generally results in a greater climate benefit than the two alternative uses considered. If marginal electricity is generated from coal, DAC is no longer the most environmentally favorable option under either current or future technology performance levels. In the case of natural gas-based marginal electricity, the level of carbon removal achieved via DAC is slightly lower than the level of carbon avoidance achieved through district heating. Nevertheless, in a future scenario with reduced energy demand for DAC, the technology could outperform the natural gas case from an environmental perspective.

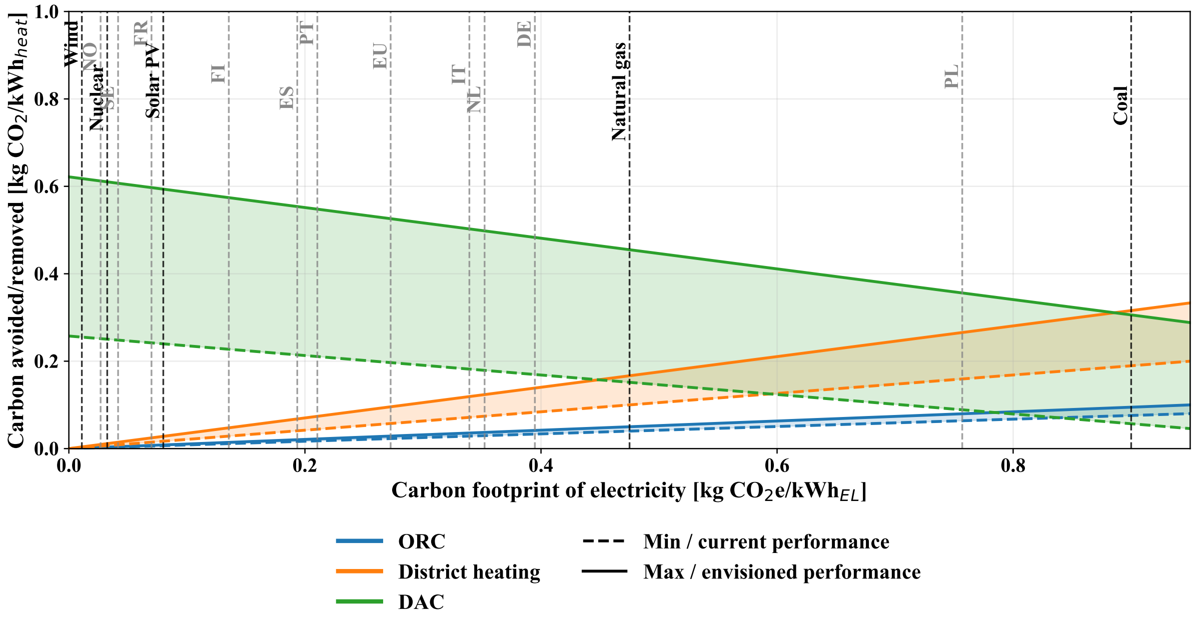


Figure 15: Environmental trade-offs associated with using heat at 100 °C to: remove CO_2 from air via DAC; generate electricity via an organic Rankine cycle; and supply heat to a district heating network which can replace a heat pump.

1.11 Application of DAC-derived technologies for dilute flue gas CO_2 capture

The results presented in this section address **RQ II** and are based on the sequential process-to-techno-economic modeling framework described in Sections 3.1 and 3.2 (**Paper III**), applied to three carbon capture technologies (ALK-ABS, MEA scrubbing, and TVSA) across a range of CO_2 concentrations (0.5%–4%) and flue gas flow rates (25–2,700 t/h), to achieve net-zero direct emissions. This section investigates: 1) alternative application opportunity, i.e. the conditions under which DAC-derived technologies applied to point-source capture in industries with CO_2-lean flue gases achieve carbon avoidance costs that are competitive with conventional CCS and current CDR credit prices; and 2) a financing opportunity conditions under which purchasing CDR credits becomes more economical than onsite capture for smaller-scale or lower-concentration sources, thereby supporting early DAC deployment. Costs are assessed on both FOAK and NOAK bases, representing the short-term and medium-term perspectives, respectively.

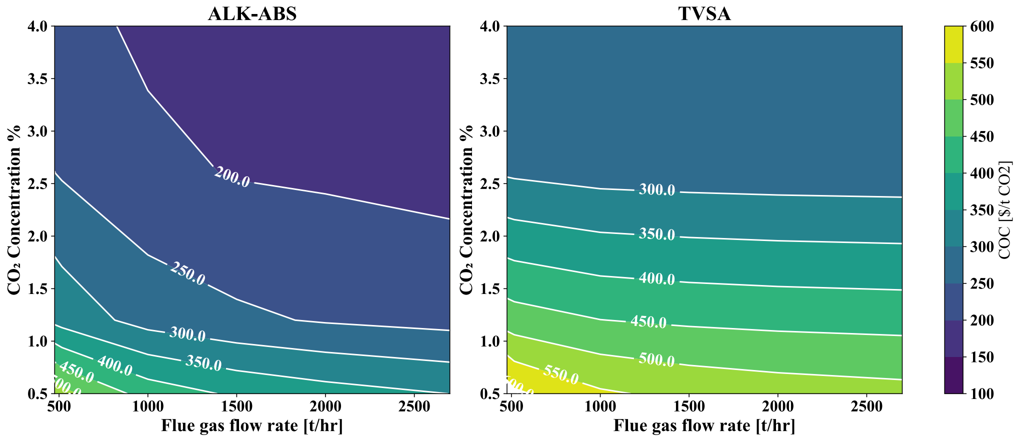
1.11.1 Cost of capture

Figure 16 shows the COC values for the three technologies considered, applied to flue gas flow rates >500 t/hr. The top row shows FOAK estimates for ALK-ABS and TVSA, while the bottom row compares all three technologies on a NOAK basis.

For NOAK, although costs do not differ strongly, MEA consistently exhibits the lowest COC among the three technologies in most of the flowrate-concentration window considered, reflecting its favorable monolithic scaling behavior, whereby specific costs decline substantially with increasing flow rate/plant size.

For TVSA, the modular nature of the technology means that specific costs scale approximately linearly with the flue gas flow rate, limiting the economies of scale that benefit MEA at higher throughput rates. As a result, TVSA exhibits generally highest COC at high flow rates. Regarding ALK-ABS, the most-expensive components, namely the air contactor and pellet reactor, exhibit near-linear scaling, resulting in overall costs that are higher than those for MEA across the parameter space. While ALK-ABS benefits from cost reductions when transitioning from FOAK to NOAK, this reduction is limited because the baseline scale for learning is higher than it is for TVSA (500 kt for ALK-ABS versus 4 kt for TVSA). Notably, under NOAK conditions, the cost gap between ALK-ABS and TVSA narrows considerably at high flow rates and high CO_2 concentrations. At CO_2 concentrations approaching 0.5%, TVSA achieves the lowest COC, reflecting the more-favorable performance of the TVSA process under dilute CO_2 conditions.

a) First-of-a-kind



b) Nth-of-a-kind

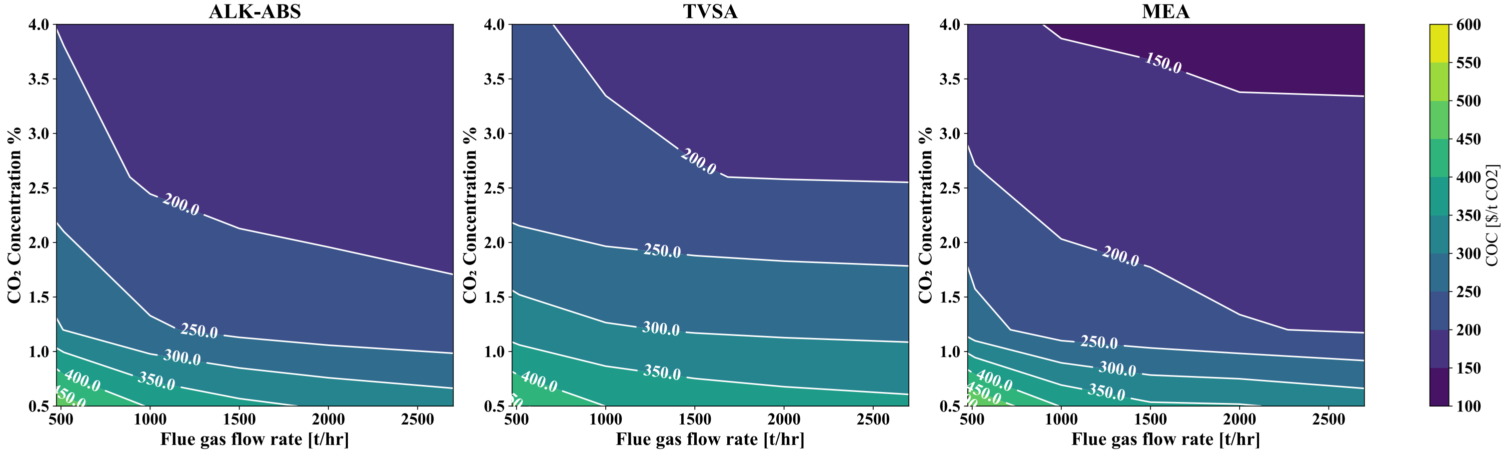


Figure 16: Cost of capture (COC) as a function of the CO_2 concentration and flow rate of the flue gas for: a) a First-of-a-kind basis; and b) Nth-of-a-kind basis. Source: **Paper II**

Figure 17 shows the COC values (and their corresponding technology) for both the FOAK (Figure 17a) and NOAK (Figure 17b) bases, for flue gas flow rates <500 t/hr (as MEA exhibits the lower costs for higher flowrates). At these smaller scales, the cost differences between technologies become more sensitive to their scaling behavior.

Under FOAK conditions, at flow rates <100 t/hr, the scaling advantage of MEA is lost and its cost increases sharply. For flow rates <50 t/hr, which are representative of small silicon production facilities and paint shops, TVSA shows the lowest COC across all CO_2 concentrations studied. The modular nature of TVSA, which eliminates scale penalties at low throughput rates, translates directly into a cost advantage at such small scale. ALK-ABS achieves the lowest COC for a narrow window of CO_2 concentrations of 0.5%–1.0% and flow rates of 100–200 t/hr, corresponding to large-scale breweries and smaller silicon production plants. Outside this window, MEA exhibits the lowest COC, followed by ALK-ABS and TVSA.

On a NOAK basis, the COC experiences a significant decrease for the less-mature DAC-based technologies, Due to learning effects. and improved modular deployment TVSA experiences a significant cost reduction, leading to substantial expansion of the region where it exhibits the lowest COC, particularly at CO_2 concentrations <1% or flowrates <200 t/hr. Notably, the region in which ALK-ABS previously offered the lowest COC under FOAK conditions disappears entirely under NOAK conditions, as the greater cost reductions achieved by TVSA render it consistently cheaper across the range of low CO_2 concentrations and moderate flow rates previously found to be favorable for ALK-ABS. In contrast, MEA benefits less from cost reductions at small scales due to its monolithic scaling, which limits flexibility and leads to higher specific costs when operated far from its optimal design capacity.

The irregular shape of the boundary between the cost-optimal technologies, which becomes more pronounced when transitioning from FOAK to NOAK, is attributed to the non-linear trade-off in the MEA process between the capture rate required to achieve near-zero emissions and the heat demand. The combination of these opposing effects leads to a local maximum heat demand for MEA at around 2.6% CO_2, yielding to the non-linear boundary shape in Figure 17b.

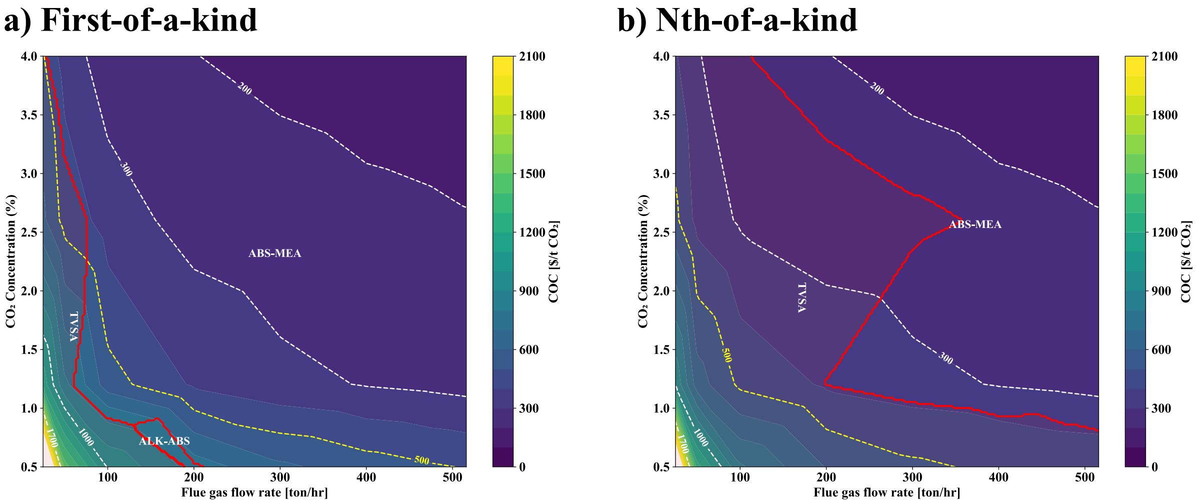


Figure 17: COC for a) First-of-a-kind and b) Nth-of-a-kind, as a function of the flue gas flow rate for the three technologies investigated. Each region is labeled according to the technology exhibiting the lowest COC within that region. Source: **Paper III**.

1.11.2 Carbon avoidance cost

The carbon avoidance cost (CAC) reflects not only the scaling characteristics discussed in the context of the cost of capture, but also the carbon footprint of the energy supply [Eq. (10)]. Each of the three technologies evaluated exhibits a distinct sensitivity to these indirect emissions. ALK-ABS shows no dependence on the carbon footprint of the heat supply (as this occurs through oxyfuel combustion in the calciner and thus all of the CO_2 generated is captured), and has a low dependence on electricity supply (which is relatively small, and consumed primarily by the air separation unit, fans, and pumps). MEA scrubbing shows strong dependence on the heat carbon footprint due to the large reboiler duty for solvent regeneration, and very low dependence on electricity. TVSA depends on the carbon footprints of both heat and electricity, exhibiting greater sensitivity to heat, reflecting the high heat-to-electricity ratio of the sorbent regeneration step.

Figure 18 presents the CAC (on a FOAK basis) for the three technologies applied to four representative industrial cases: a small-scale silicon production facility (25 t/h, [CO_2] 1.2%), a large-scale iron ore pelletization plant (500 t/h, [CO_2] 2.6%), a medium-scale aluminum production facility (1,000 t/h, [CO_2] 1.2%), and a natural gas combined cycle (NGCC) plant (2,700 t/h, [CO_2] 4%), across heat supply options and country-specific electricity mixes for Germany, Poland, Spain, and Sweden. Boxes marked with a red cross indicate combinations for which no net CO_2 avoidance is achieved.

As shown in Figure 18, ALK-ABS achieves the lowest CAC for silicon production, iron ore pelletization, and aluminum production across most of the combinations, since its insensitivity to the heat carbon footprint makes coal and natural gas calciners viable without penalizing net avoidance. MEA scrubbing achieves competitive CAC for NGCC, mainly due to the availability of low carbon heat (as low-pressure steam can be extracted directly from the plant). TVSA consistently shows the highest CAC across all four industries, with the gap being most-pronounced at high flow rates and higher CO_2 concentrations, under which conditions MEA and ALK-ABS derive greater benefits from economies of scale.

Across all the technologies, Poland consistently shows the highest CAC values, while Sweden achieves the lowest CAC, directly reflecting their contrasting electricity carbon intensities. This pattern is particularly evident for the electrified heat supply options, such as the electric calciner for ALK-ABS, the electric boiler for MEA scrubbing, and the heat pump for TVSA, which are not feasible or among the most-expensive options in Poland, yet competitive or even optimal in Sweden. This pattern breaks for the case of NGCC as low carbon heat and electricity would be available onsite. The strong impact of carbon footprint of electricity on the CAC of electrified technologies highlights an important interaction between technology development and development of low-carbon energy system: electrification of the heat supply is a promising pathway towards reducing the carbon footprint of capture processes, although its effectiveness is contingent upon the availability of low-carbon electricity (Figure 1). In a carbon-intensive grid, electrification can, paradoxically, increase indirect emissions and thereby the CAC relative to fossil-fueled alternatives, undermining the environmental case for what is commonly perused as technically to environmental performance of the technology. This highlights that technology-level advances and development of low-carbon energy system are not independent. The deployment of electrified capture configurations should be prioritized in regions where the emissions electricity grid is already largely mitigated, while fossil-fueled but CO_2-capturing configurations, such as the oxyfuel calciner in ALK-ABS, may remain preferable in the near term at other locations.

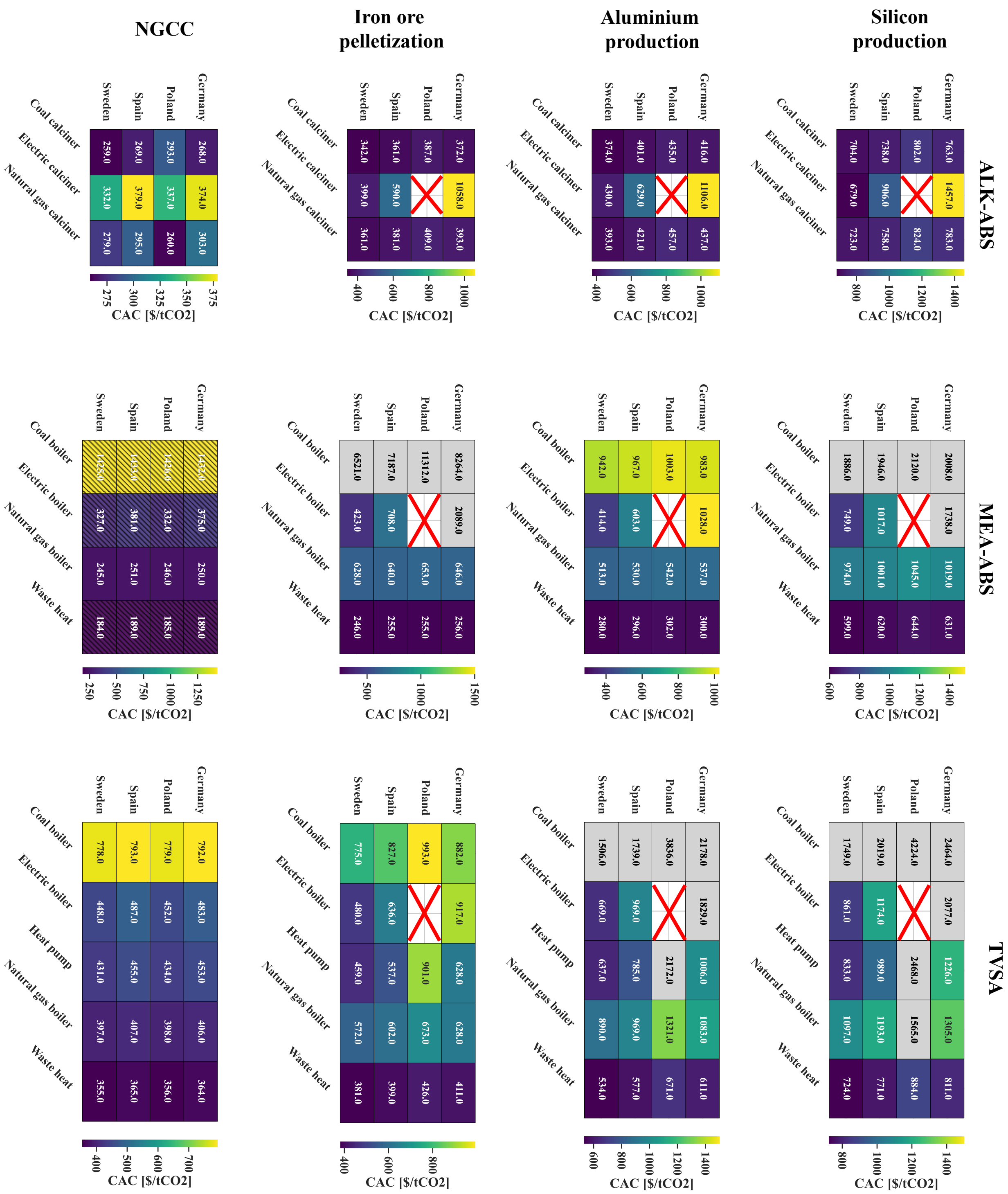


Figure 18: First-of-a-kind carbon avoidance cost (CAC) as a function of the carbon footprint of the heat and electricity supply, for different countries and heat provisions assuming cost of transport and storage of 105 \$/tCO_2, for the cases of: silicon production (100 t/h, 10 kt/a, [CO_2] = 1.2%, small scale[108]); aluminum production (1,000 t/h, [CO_2]=1.2%, approx. 125 kt/a aluminum[109], medium scale); iron ore pelletization (500 t/h, [CO_2]=2.6%, approximately 5 Mt/a[110], large scale); and natural gas combined cycle (NGCC) (2,700 t/h, [CO_2]=4%, approximately 500 MW[111]). Cells with costs above the highest CDR credit price available (1,500 \$/tCO_2) are colored in gray. cells marked with a red cross indicate combinations for which no net CO_2 avoidance is achieved Cells corresponding to non-relevant combination for the NGCC are hatched. Note the different scales for the color gradients. Source: **Paper III**.

The lowest CAC for each industry can be compared with CDR credit prices to inform the choice between onsite point-source capture and the purchase of offsets. This work considers only CDR credits that provide permanent storage, supplied via DAC. A benchmark range of 400–600 \$/tCO_2 is adopted based on current market prices obtained from the main providers, Climeworks (600–1,000 \$/tCO_2), and Carbon Engineering (395 \$/CO_2).

For NGCC, onsite MEA scrubbing is more cost-effective than purchasing current CDR credits. For iron ore pelletization and aluminum production, the estimated CAC falls below or within the CDR credit price range, making capture economically competitive, although uncertainty linked to the cost estimates prevents a definitive conclusion. For silicon production, purchasing CDR credits is the lower-cost option.

The dependence of the CAC to scales and concentrations can become a significant aspect in the choice between capturing and off-setting: while larger silicon facilities than those considered here are still expected to yield CAC above the CDR credit prices (thus, keeping off-setting as cheapest option), smaller iron ore pelletization plants than the case considered here would yield a CAC above the CDR credit range (thus shifting the cheapest option from capturing to off-setting).

Figure 19 shows the CAC values, on a NOAK basis, for the three technologies applied to the four representative industries. Figure 19 also assumes a low cost of 35\$/tCO_2 for the transportation and storage representing the developed infrastructure for NOAK case. The shift from FOAK (Figure 18) to NOAK (Figure 19) basis implies considerable differences in the competitive landscape, reflecting the stronger cost reductions projected for the less-mature technologies. ALK-ABS remains the lowest-cost option for aluminum production and iron ore pelletization across most of the heat supply and country combinations, retaining its advantage from the oxyfuel calciner. However, under NOAK conditions, for silicon production, TVSA becomes competitive and even outperforms ALK-ABS, particularly in low-carbon electricity countries such as Sweden, as the projected learning-driven cost reductions disproportionately benefit the more-modular TVSA technology. For NGCC, MEA scrubbing continues to yield the lowest CAC and remains competitive under a low-carbon heat supply.

Across all the investigated industries and technologies, the NOAK cost reductions narrow the gap between the technologies, making the choice increasingly sensitive to site-specific conditions rather than being dominated by a single technology. Further, the CAC remains lower than the costs of removing CO_2 via DAC (1,030 \$/tCO_2 for S-DAC and 809 \$/tCO_2 for L-DAC), i.e. reaching net-zero direct emissions via capture onsite is in the medium-to-long term more economic than offsetting CO_2 via DAC.

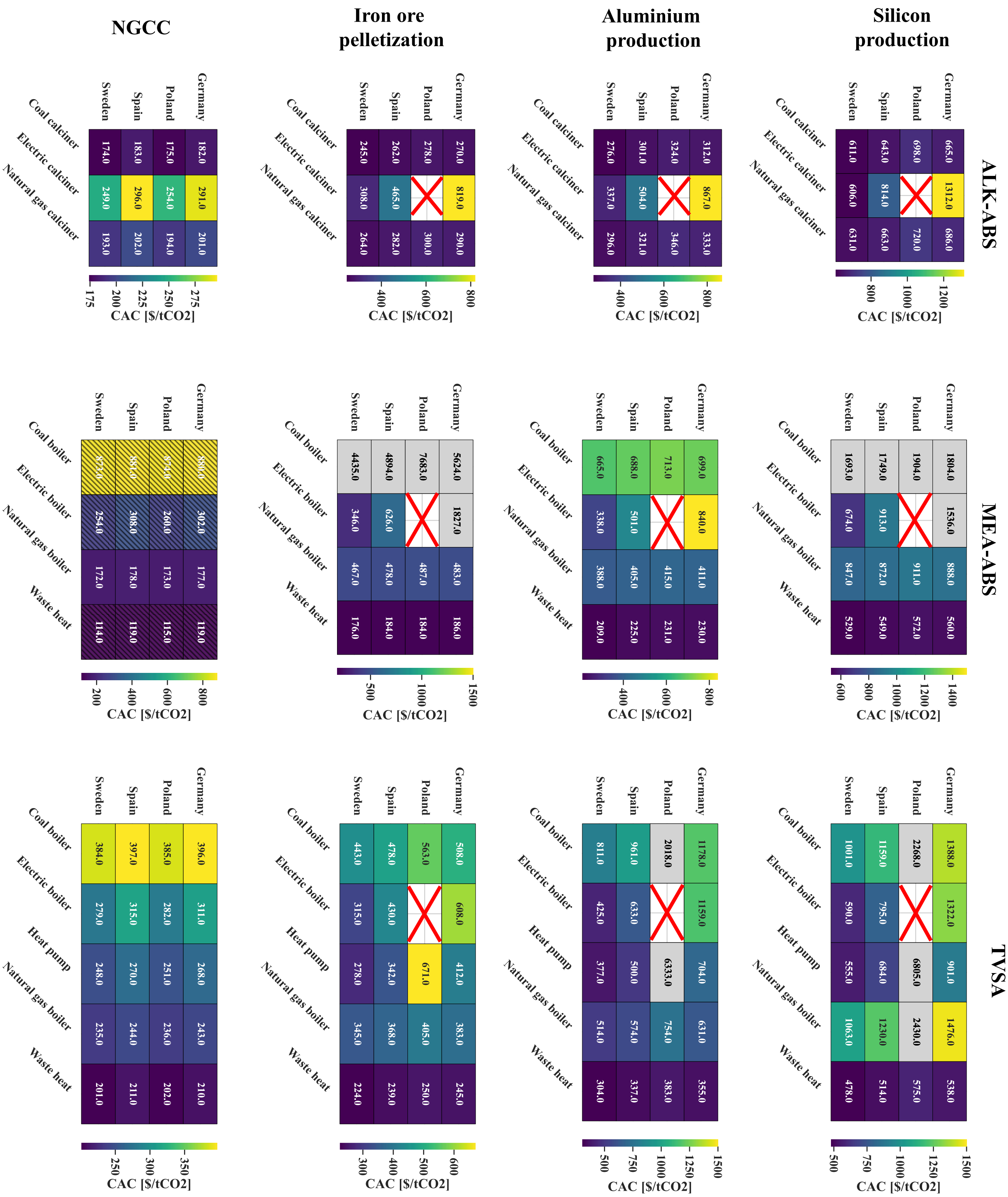


Figure 19: Nth-of-a-kind carbon avoidance cost (CAC) as a function of the carbon footprint of the heat and electricity supply, for different countries and heat provisions, for the cases considered. NGCC, Natural gas combined cycle. The CAC is assessed for cost transport and storage of 35 \$/tCO$_2$.

1.11.3 Process efficiency

To complement the economic assessment, the thermodynamic performances of the three technologies considered are evaluated using the energy and exergy efficiency metrics defined in Chapter 2, providing a basis for assessing whether reaching net-zero direct emissions via point-source capture from CO_2-lean flue gases thermodynamically outperforms removing atmospheric CO_2 via DAC.

Figure 20 shows the results for the thermodynamic performances of the considered processes from the energy [Eq. (6)] and exergy [Eq. (8)] perspectives. All three technologies show increasing energy and exergy efficiencies with increasing inlet CO_2 concentration. This is consistent with the thermodynamic expectation that separation becomes less work-intensive at higher concentrations. From the energy efficiency perspective, TVSA performs best among the point-source technologies studied and is comparable to the S-DAC benchmark at atmospheric concentrations of CO_2. From the exergy perspective, both MEA and TVSA outperform S-DAC, while ALK-ABS shows the lowest exergy efficiency.

In summary, none of the point-source capture configurations studied can be classified as thermodynamically hard-to-abate at any CO_2 concentration higher than the atmospheric concentration. Thus, reaching net-zero direct emissions via capturing CO_2 from a concentrated source with high capture rates becomes more thermodynamically efficient than removing it from the air. This provides thermodynamic support for the argument that, in general, point-source capture should be prioritized over atmospheric CDR wherever feasible (see Figure 1).

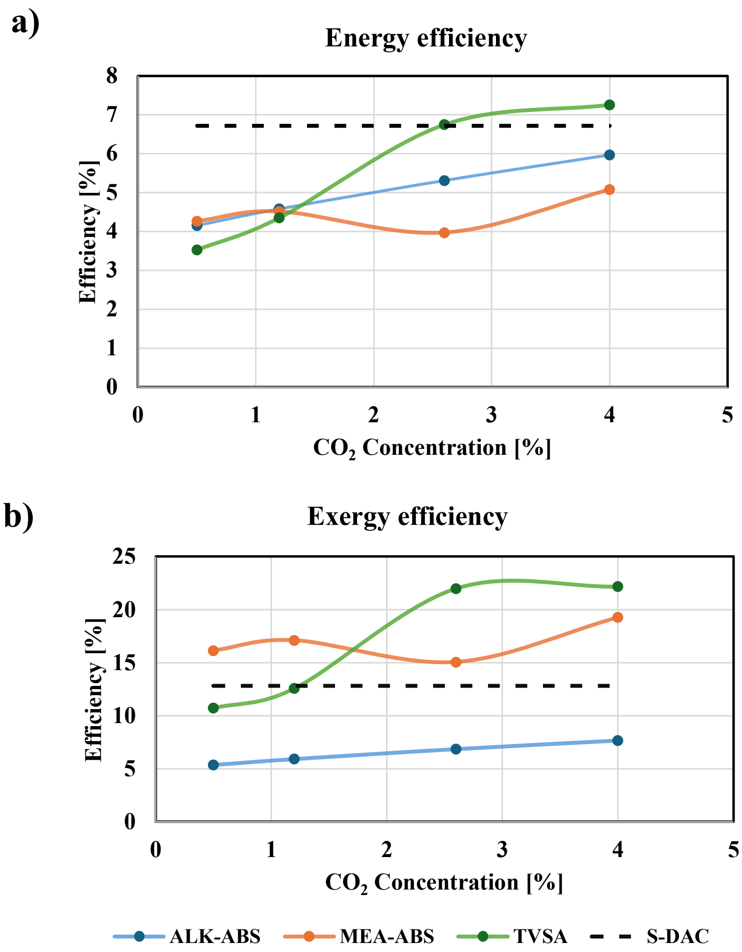


Figure 20: Efficiencies of the capture step in terms of a) energy (Eq. 6) and b) exergy (Eq. 8), for the three point source capture processes considered. Efficiency for direct air capture via solids adsorption is provided as reference (dashed line). Data shown are for a flue gas flow rate of 1,000 t/h. Source: **Paper III**.

1.12 Application of DAC-derived technologies for post-capture CO_2 polishing

The results presented in this section address **RQ III** and are based on the same sequential process-to-techno-economic framework used in Section 4.2 (**Paper IV**), applied to industries that generate CO_2-rich flue gases (4%–20%) at a fixed flow rate of 10,600 kmol/h. Three configurations are considered to achieve net-zero direct emissions:

i. Stand-alone MEA scrubbing operated at high capture rates;
ii. MEA scrubbing combined with external DAC offsetting, where residual emissions are compensated through purchased CDR credits;
iii. MEA scrubbing followed by a TVSA polishing step capturing the remaining CO_2 fraction.

This section investigates both an alternative application opportunity (the conditions under which the MEA+TVSA polishing configuration achieves a lower CAC than stand-alone MEA) and a financing opportunity (the conditions under which purchasing CDR credits generated via DAC is more economical than onsite capture, thereby supporting early DAC deployment).

1.12.1 Cost of stand-alone MEA at high capture rates

The CAC (Figure 21a) and marginal CAC (Figure 21b) are calculated as functions of the inlet CO_2 concentration and capture rate. Achieving net-zero emissions exclusively via deep MEA operation requires capture rates >99% (corresponding to the last data point in each series plotted in Figure 21b), which results in CAC values in the range of 270–350 $/t$CO_2$. These increased costs are mainly driven by the prices and carbon intensities of electricity and regeneration heat, which is assumed to be supplied by an auxiliary natural gas boiler without CO_2 capture, along with transport and storage costs (50 $/t$CO_2$). For any given inlet concentration of CO_2, the CAC varies only modestly for capture rates between 90% and approximately 97%–98%. The minimum CAC (194–285 $/t$CO_2$) occurs at capture rates that decrease with increasing CO_2 concentration, from 97% at 4% CO_2 to 90% at 20% CO_2, reflecting the trade-off set by CO_2 concentration: improved thermodynamics for separation efficiency on one side, but higher absolute capture required for net-zero on the other side. As shown in Figure 21b, the marginal CAC remains relatively stable over most of the capture range but rises sharply beyond 97%–99%. This increase is primarily due to a steep rise in the specific reboiler duty required to capture the final fraction of the residual emissions. At higher inlet CO_2 concentrations, the increasing capture rates raise the peak solvent temperatures, requiring higher circulation rates to maintain absorption performance. As the thermodynamic and mass-transfer limits are approached, any additional capture becomes increasingly energy-intensive, driving up the marginal costs.

These results indicate that MEA capture remains cost-effective within the range of 65–350 $/t$CO_2$ up to a capture rate of about 97%–98%. Beyond this level, the costs escalate rapidly and can exceed the upper range of the costs for CDR via DAC (2,000 $/t$CO_2$). In addition, achieving net-zero becomes more expensive at higher inlet CO_2 concentrations, due to the much higher absolute level of capture required. Overall, for achieving net zero, these results support investigating alternatives in which MEA is deployed to stand up to 97% capture and the remaining emissions are addressed through complementary CO_2 removal approaches, such as DAC offset (MEA+DAC offset) or DAC-inspired capture (MEA+TVSA polishing).

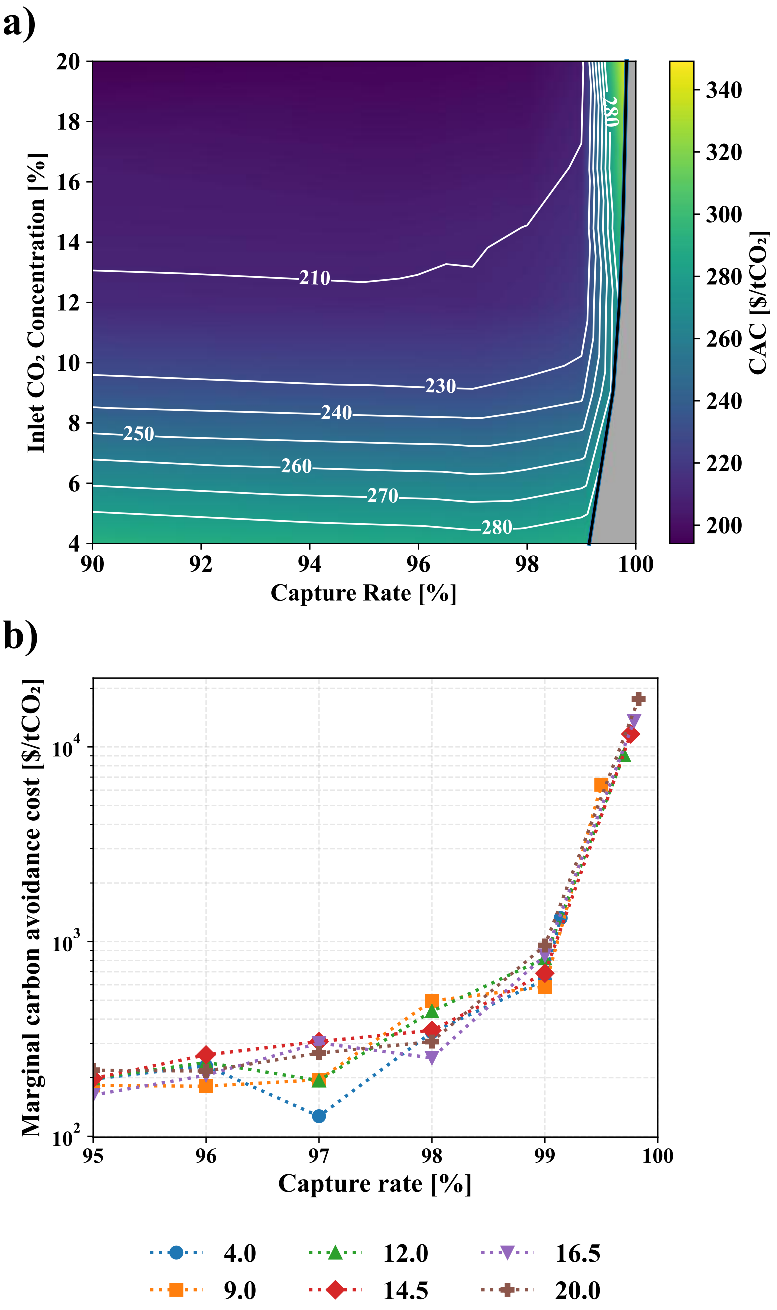


Figure 21: Carbon avoidance cost (CAC) and marginal CAC for MEA scrubbing, for different inlet CO_2 concentrations and capture rates. Source: **Paper IV**.

1.12.2 Comparison of net-zero configurations

Figure 22 compares the costs of achieving net-zero direct emissions across the three configurations considered. In the MEA+TVSA polishing and MEA+DAC offset cases each datapoint reflects an independently optimized MEA capture rate, whereas in the stand-alone MEA case, the required capture rate is dictated by the inlet CO_2 concentration.

For stand-alone MEA, the cost initially decreases as the inlet CO_2 concentration increases from 4% to 9%, and this is followed by an increase at higher CO_2 concentrations due to the higher capture rates and associated energy demand needed to reach net-zero emissions. As a result, the minimum cost is seen at a CO_2 concentration of approximately 9%. Overall, stand-alone MEA tends to be more expensive than the hybrid configurations, although the difference diminishes at lower concentrations. At 4% CO_2, all three configurations converge to a similar cost level, since achieving net-zero requires a capture rate of 99.14%. With MEA already capturing nearly all of the emissions, only a very small residual fraction (0.14%) remains to be addressed, leading to negligible differences between extending MEA capture, applying TVSA polishing or offsetting via DAC. The difference between standalone MEA and the other configurations increases sharply as the inlet CO_2 concentration increases, , as presented in Figure 22, due to fast-growing marginal cost for standalone MEA at high capture rates.

In contrast, both hybrid configurations exhibit decreasing costs with increasing CO_2 concentration. Among them, the MEA+TVSA polishing option consistently achieves the lowest cost, while the MEA+DAC offset case has an intermediate cost. This advantage stems from the higher CO_2 concentration in the flue gas entering the polishing step, which improves separation efficiency. In comparison, DAC operates at atmospheric CO_2 levels, resulting in inherently higher energy requirements and, consequently, higher costs.

Delving deeper into each configuration for MEA+DAC offset, the cost-optimal capture rate of the MEA unit remains constant at 99% due to the high costs of offset via DAC. In contrast, with respect to the cost-optimal capture rate for the MEA+TVSA polishing option, the MEA capture rate varies with inlet CO_2 concentration, e.g., 99.14% capture for 4% CO_2, 97% capture for 4.0%–14.5% CO_2, and 98% capture for 16.5%–20.0% CO_2, leaving 2%–3% of the $CO_2$for residual capture through TVSA polishing.

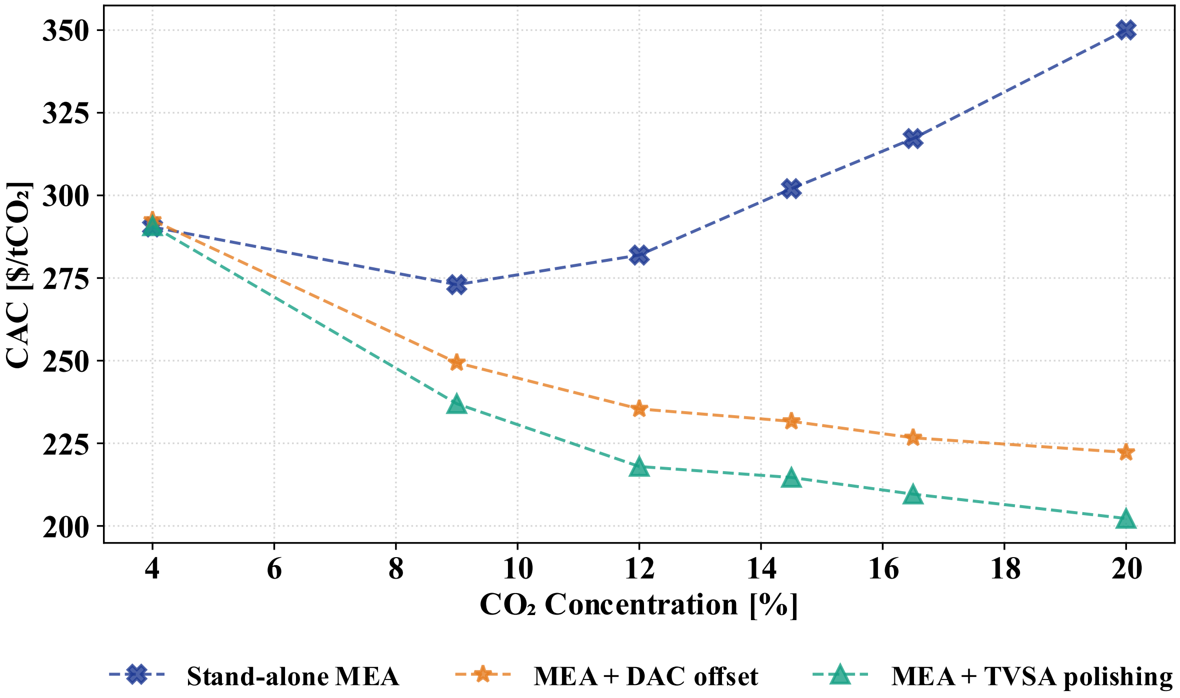


Figure 22: Carbon avoidance cost (CAC) as a function of the inlet CO_2 concentration for the three net-zero configurations considered. It should be noted that in the hybrid configurations, each datapoint represents an independently optimized MEA capture rate, whereas in the stand-alone MEA case, the required capture rate is dictated by the inlet CO_2 concentration. Source: **Paper IV**.

1.12.3 Sensitivity to electricity price and carbon intensity

Figure 23 illustrates the impacts of electricity price (Figure 23, a and b) and electricity carbon footprint (Figure 23, c and d) on the cost-optimal technology choice. In Figure 23, a and c, all configurations are assumed to operate under EU-average electricity conditions, i.e., a price of 105 \$/MWh and a carbon footprint of 0.272 tCO_{2eq}/MWh. In contrast, Figure 23, b and d reflect the geographic flexibility of DAC, assuming access to electricity that is either cheaper (39 \$/MWh) or cleaner (0.0152 tCO_{2eq}/MWh) than that available to the onsite capture systems.

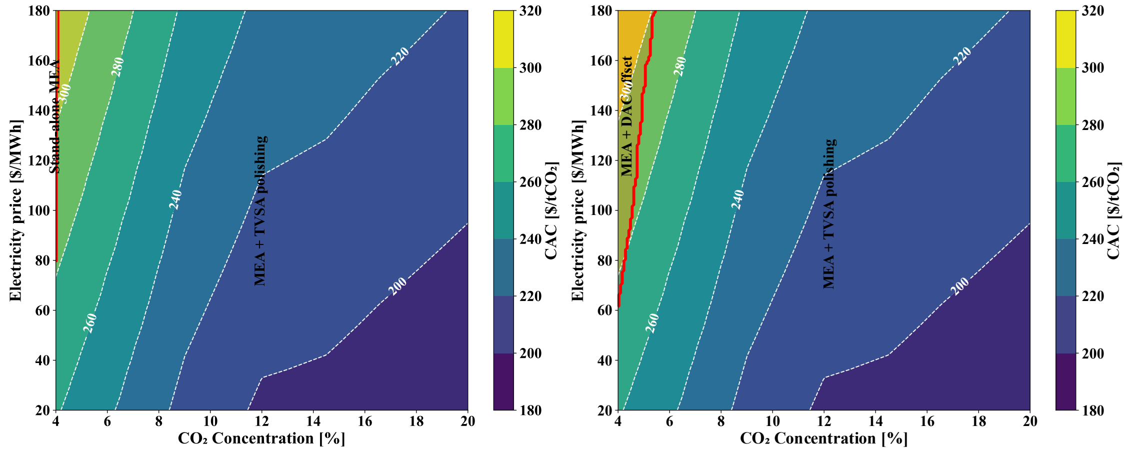
Under EU-average electricity conditions (105 \$/MWh, 0.272 tCO_{2eq}/MWh), MEA+TVSA polishing is the lowest-cost option over almost the entire parameter space. Stand-alone MEA becomes competitive only in a narrow window of very low CO_2 concentrations (around 4%) in combination with high electricity prices (>80 \$/MWh) and/or high carbon intensities (>0.6 tCO_{2eq}/MWh). These are conditions under which the electricity-intensive TVSA polishing step becomes relatively more costly.

When DAC is assumed to have access to cheaper electricity (39 \$/MWh, reflecting regions with surplus renewable generation) the MEA+DAC offset configuration becomes competitive with stand-alone MEA in the low-concentration/high-price window and extends its competitiveness to slightly higher concentrations (around 5%). When DAC has access to cleaner electricity (0.015 t CO_{2eq}/MWh, for example in Iceland or Norway), the MEA+DAC offset configuration becomes the lowest-cost option across a broader range, particularly for CO_2 concentrations of between 4% and 9% in combination with high onsite carbon intensities. Notably, access to low-carbon electricity creates a larger opportunity window for the DAC offset configuration than access to cheap electricity, reflecting the strong influence of the carbon footprint on the competitiveness of atmospheric CDR.

Taken together, these results highlight that the competitiveness of DAC-derived configurations is strongly governed by both the electricity price and carbon intensity, and thus by the flexibility to locate DAC systems in regions with favorable energy conditions.

a) **EU average carbon footprint of electricity for all cases**

b) **Same as a) with cheaper electricity available to DAC**



c) **EU average price of electricity for all cases**

d) **Same as a) with cleaner electricity available to DAC**

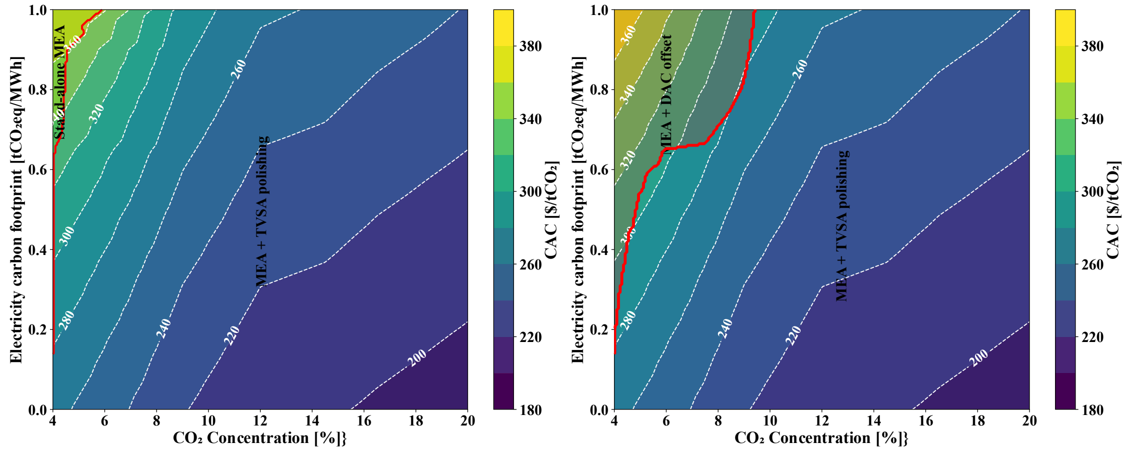


Figure 23: Effects of electricity prices and carbon footprints of electricity on the choice of cost-optimal technology. Heat maps show the lowest-cost configuration (stand-alone MEA, MEA+DAC offset, MEA+TVSA polishing) across the ranges of electricity prices and carbon intensities. Panels **a)** and **c)** assume identical EU-average levels (in terms of carbon footprint and price, respectively) of electricity for all technologies, while panels **b)** and **d)** reflect the geographic flexibility of DAC achieved through access to cheaper electricity and cleaner electricity, respectively. The boundaries indicate shifts in the preferred configuration. Source: **Paper IV**.

1.12.4 Net-zero design considerations for carbon capture units

The results presented here substantially reduce the anticipated role of DAC as a CDR option for compensating residual industrial emissions. Previous assessments often assumed that DAC would offset approximately 10% of the emissions remaining after conventional capture rates of 90%. However, the findings of this work show that, with cost-optimal net-zero configurations, residual emissions are reduced to around 1% following high-rate capture by MEA scrubbing. This corresponds to a reduction of roughly 90% in the projected demand for CDR from industrial point sources, compared to the widely accepted benchmark of a 90% capture rate. Moreover, under most conditions the 1% residual is shown by the results above to be most cost-effectively handled by on-site TVSA polishing rather than atmospheric DAC, further reducing the role of atmospheric CDR in the industrial emissions reduction portfolio.

Instead, hybrid configurations that combine high-rate MEA capture with DAC-inspired TVSA polishing show strong potentials for achieving net-zero direct emissions. In such systems, the polishing step typically captures only 2%–3% of the total emissions, benefiting from higher CO_2 concentrations than atmospheric air and, therefore, offering clear thermodynamic and economic advantages. Across all of the configurations analyzed, the cost-optimal MEA capture rate is never below 97%, indicating a clear design implication: net-zero systems are recommended be engineered for capture rates of at least 97%, and preferably for higher capture rates where required. These systems may either integrate polishing units from the outset or be designed so as to allow retrofitting as adsorption-based technologies mature.

Even if MEA+DAC-inspired TVSA polishing emerges as the least-cost configuration under projected future costs (NOAK basis), it should be noted that its current technology maturity level makes it not yet fully competitive with other capture configurations. Designing CCS installations in a "polishing-ready" format would enable incremental retrofits as the adsorption technologies mature, preserving long-term flexibility while supporting scalable industrial emissions reduction. In the short term, the only two options remaining would be stand-alone MEA and MEA+DAC offset, where the offset part can be provided through the purchase of CDR credits for removal in the future, providing a financing opportunity for DAC and DAC-derived technologies.

Discussion

This chapter synthesizes and reflects on the findings of Papers II, III, and IV in three sections.

Section 5.1 summarizes the results from all three papers and map the opportunity landscape for DAC and DAC-derived technologies.

Section 5.2 examines the key uncertainties in the results.

Section 5.3 interprets the overall findings from boarder perspectives.

1.13 Summary of the results

1.13.1 DAC cost and future cost

Figure 24 shows the cost projections for the S-DAC and L-DAC technologies (data used for generation of the figure is given in Tables 3-5 the *Appendix*). showing that currently projected DAC costs are high and will remain so in the near term, making costs the main challenge for the technology. The costs projected in this thesis show that S-DAC costs will reach 560 $/tCO_2$ and 1,030 $/tCO_2$ at 1 Gtpa and 1 Mtpa cumulative deployment, respectively, and L-DAC costs will reach 430 $/tCO_2$ and 870 $/tCO_2$ at the same respective deployment levels. This reflects progress along the learning curve, although the costs will not approach those of conventional mitigation options.

Policy with respect to DAC has been shaped to meet cost targets. Most notable in this context is the U.S. Department of Energy's 100 $/CO_2$ goal, which is not supported by state-of the-art cost projections [112]. While DAC costs will likely decline with increased deployment, the pace and extent of that decline remain uncertain, and near-term applications must be justified based on costs that are likely to remain above 400 $/tCO_2$ in the baseline case and not below 250 $/tCO_2$ in the optimistic case for the foreseeable future.

Even at these costs, DAC has feasible applications in the three contexts investigated in this thesis, all of which identify conditions under which DAC or DAC-derived technologies are cost-competitive within short-term and medium-term horizon. These conditions can be exploited to drive the technology further along the learning curve and reduce the capital costs.

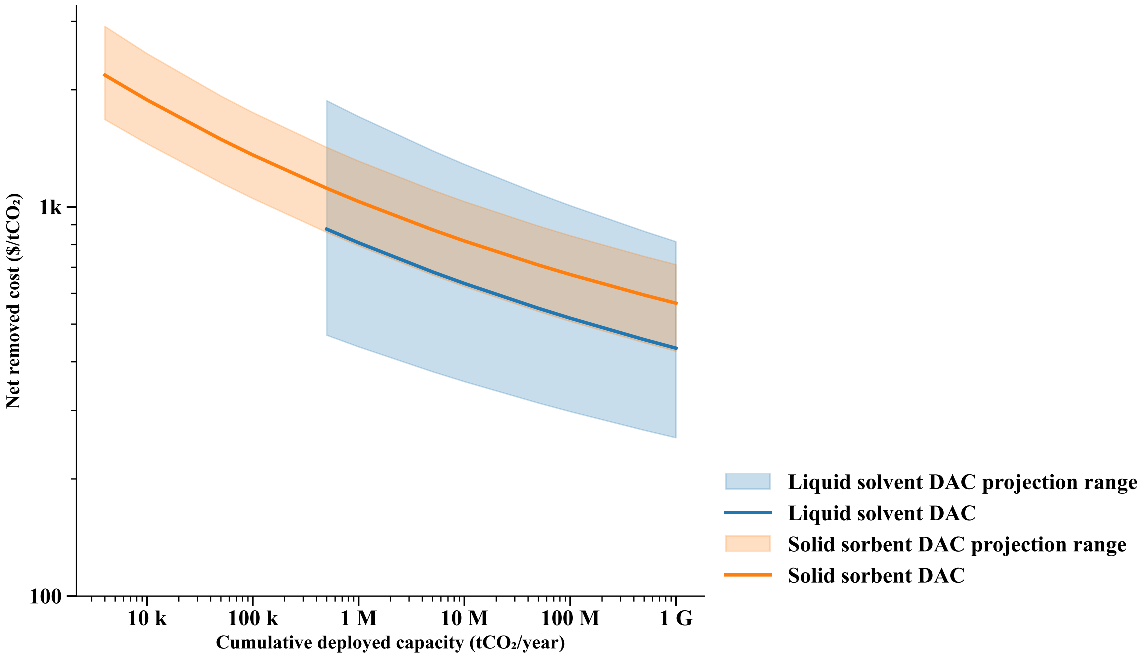


Figure 24: Projected cost estimates for S-DAC and L-DAC as a function of the cumulative deployment capacity.

1.13.2 Opportunities for DAC and DAC-derived technologies

The three research questions investigated in this thesis map a coherent opportunity landscape for DAC across three categories: direct implementation, alternative application, and financing opportunities spanning over two time horizons.

The cost assessment results show that ,in the short term, the most-viable direct implementation opportunity is CHP-integrated DAC in district heating systems that have access to a CO_2 transport infrastructure (**RQ I**), where CDR via PCC and DAC jointly generate sufficient revenue to justify the investment at current CDR credit prices. For industries with CO_2-lean flue gases (**RQ II**), point source capture using DAC-derived technologies represents a viable application opportunity for medium-scale sources that contain CO_2 concentrations of 1%–4%, where CAC falls within or below the current CDR credit price range. For smaller-scale or lower-concentration sources, purchasing CDR credits constitutes a financing opportunity, supporting early DAC deployment while providing a near-term compliance pathway for industries that cannot yet justify onsite capture. For high-concentration sources (**RQ III**), the short-term choices are stand-alone high-rate MEA or MEA combined with CDR credit purchasing for residual emissions, with the latter representing a financing opportunity for DAC scale-up. Both cases require that CDR credit prices remain within the 400–1,000 $/tCO$_2$ range, which is currently the case, although it cannot be assumed to remain so indefinitely.

The cost assessment results show that in the medium term, NOAK cost reductions, which are large for TVSA and ALK-ABS, significantly expand the alternative application opportunity. Point source capture from previously hard-to-abate industries becomes cost-competitive across a wider range of scales and concentrations, and MEA combined with TVSA polishing emerges as the dominant net-zero configuration for high-concentration sources as the TVSA technology matures. Thus, the financing opportunity created by near-term CDR credit purchasing funds the technology learning that enables the medium-term alternative application opportunity, representing a positive feedback loop between market demand and cost reduction that justifies not treating near-term CDR credit purchasing as a permanent alternative to capture, but as a transitional instrument.

1.13.3 Identification of hard-to-abate emissions

This thesis quantitatively determines the boundaries of hard-to-abate and abatable emission sources through the method of using DAC cost and exergy demand as metrics, by applying it across a range of CO_2 concentrations and capture extents[5]. A distinction is drawn between thermodynamically hard-to-abate emissions (where the exergy requirement of point source mitigation required for achieving net-zero surpasses that of DAC) and economically hard-to-abate emissions (where the cost of point source mitigation surpasses that of CDR via DAC).

From the thermodynamic perspective, none of the point-source capture configurations studied in **Papers III** and **IV** can be classified as hard-to-abate relative to the DAC benchmark. Energy and exergy efficiencies increase monotonically with inlet CO_2 concentration across all three technologies, confirming that reaching net-zero via point source capture is thermodynamically preferable to atmospheric CDR wherever it is technically feasible. This provides a thermodynamic rationale for prioritizing point source capture over atmospheric CDR in the emissions reduction hierarchy. This conclusion is independent of current cost levels and holds true regardless of future technological developments.

From the economic perspective, the hard-to-abate boundary depends on the scale, concentration, energy system context, and maturity of the capture technology. Under current FOAK conditions, emissions from low-concentration flue gas streams, such as those from silicon production and smaller-scale aluminum and iron ore facilities, can be classified as economically hard-to-abate, as their point source capture costs exceed the current CDR credit price range of 400–600 $\$/tCO_2$. Under NOAK conditions, however, the same industries shift towards economic viability for point source capture, particularly for TVSA in low-carbon electricity regions. The economic hard-to-abate boundary is, therefore, a moving target rather than a permanent classification, and policy instruments that use it to define offsetting obligations should be designed with this temporal dynamic in mind.

For the high-concentration flue gas streams addressed in **Paper IV**, the hard-to-abate classification does not apply to any of the cases studied, as in that point source capture consistently outperforms CDR credit purchasing across most of the parameter space.

1.14 Uncertainties linked to the results

1.14.1 Use of the CDR credit price as a metric

It is worth noting that using current CDR credit prices as a metric entails an inherent uncertainty, since the future of the CDR market and price dynamics are not clear. However, it remains the most readily available metric for benchmarking carbon removal costs. CDR credits are not a homogeneous commodity, as they differ with respect to durability, verification methodology, and the profit margins embedded in their traded price, which means that a credit price does not simply translate into an equivalent cost for carbon removal. The 400–1,000 $/tCO_2$ range used here reflects current voluntary market conditions for DAC offsets, although there are good reasons to be cautious about treating this range as stable. Markets for carbon offsets show a troubled history of misallocation, where credits have been issued for projects that would have proceeded regardless of subsidy support, calling into question whether market prices actually reflect the marginal cost of genuine CDR[113]. At the same time, the demand side is uncertain: the volumes of emissions that genuinely require offsetting may shrink which can be due to development of mitigation technologies or policy changes in the customer company e.g. Microsoft's pause in credit purchase 2026 that reduced the demand by 90%[114]. This can reduce the credit prices. On the other side, stricter additional requirements and growing corporate demand could push prices higher[115]. The practical implication is that the crossover points identified in this thesis, where purchasing CDR credits becomes more economical than onsite capture, should be understood as conditionally valid under current voluntary market conditions rather than as robust long-term thresholds. While this uncertainty does not undermine the analysis, it does reinforce the case for treating the purchase of near-term CDR credits as a transitional instrument rather than as a permanent mitigation strategy.

1.14.2 Choice of reference year

The choice of reference year can significantly affect the results of a techno-economic assessment. This work uses 2021 as the reference year, the implications of which can be understood from the perspectives of capital and operational costs.

For capital costs, the rapid evolution of DAC technologies after Year 2023, including industrial-scale data from projects such as Climeworks Mammoth, may reduce the capital cost estimates for DAC-related technologies relative to those used herein. To the extent that learning-driven cost reductions have materialized faster than anticipated, the capital costs assumed in this thesis may be on the conservative side, and the economic viability of DAC alternative applications identified here could be more favorable under updated cost assumptions. In contrast, inflation has driven up direct material costs in recent years, which can directly increase the capital costs. The net effect on capital costs thus reflects a balance between learning-driven reductions and inflationary escalation which remains uncertain.

For operational costs, using 2021 as the reference year underestimates the fuel and electricity price increases observed in Year 2022[116]. Higher energy prices increase the operating expenditures of all capture technologies, although the impact is not uniform. Energy-intensive processes, such as ALK-ABS and high-rate MEA scrubbing, are more susceptible to fuel price volatility, while the competitiveness of TVSA, the energy demand of which is dominated by electricity, depends to a greater extent on electricity price trajectories. In general, the directional effect of post-2021 energy price increases have been to raise capture costs across the board, which would shift some of the alternative application and financing opportunities identified in this thesis towards a less-favorable economic territory, particularly for short-term FOAK deployments.

1.14.3 Cost of transport and storage

The transport and storage infrastructure represents a bottleneck for the broader deployment of carbon mitigation strategies, and its cost varies considerably by location. In the absence of a CO_2 transport infrastructure or where transport and storage costs are high, DAC can leverage its locational flexibility to occupy sites close to storage locations with favorable geology and access to low-carbon energy an approach that is consistent with the siting strategy of current DAC projects. In the near term, this points to proximity to storage sites where transport requirements are minimal, or to ports where ship-based transport is accessible. As the infrastructure expands, this flexibility enables progressively more decentralized deployment, co-located with industrial waste heat or variable renewable energy, with the infrastructure developed for CCS at major point sources providing the scaffold upon which distributed DAC units can be added.

This thesis uses a transport and storage cost range of 35–175 $/tCO$_2$[117], reflecting variations in distance to storage sites and mode of transport. This range is sufficiently broad to affect the results across all three research questions.

In **Paper II**, higher transport and storage costs translate directly into higher CDR credit prices being required to make CHP-integrated DAC economically feasible, thereby narrowing the window of viability identified under favorable infrastructure assumptions.

In **Paper III**, the upper boundary of 175 $/tCO$_2$ represents 20%–60% of the CAC on a FOAK basis across the industries considered. At this cost level, purchasing CDR credits becomes the more-economical option for aluminum production and iron ore pelletization plants that are located far from storage sites. Under NOAK conditions, transport and storage costs represent a larger share of a lower total CAC, although they do not alter the fundamental conclusion: none of the industries shift from a capture-preferred to an offset-preferred outcome solely on the basis of transport and storage costs.

In **Paper IV**, higher transport and storage costs increase the absolute cost of the capture configurations studied but are not in themselves sufficient to change the directional conclusions regarding the relative merits of stand-alone MEA, MEA combined with TVSA polishing, and CDR credit purchasing.

1.15 Implications of the results

1.15.1 CCS vs DAC

Mitigation via CCS and offsetting via DAC have been regarded as a binary choice for industries. Optimistic DAC cost projections alleviate the perceived urgency surrounding CCS deployment today, while uncertain or pessimistic projections encourage more-conservative near-term mitigation[118,119]**.** Paradoxically, optimistic framing appears to be the most damaging for near term climate action. By treating CCS and DAC as substitutes rather than complements, and by assigning a deterministic quality to cost projections that are not warranted, optimistic DAC expectations is likely to actions that should be taken now. For mitigation to occur, the high end of the DAC cost range is recommended to be considered in decision-making, and the appropriate policy response to this uncertainty is to accelerate CCS deployment rather than wait for DAC costs to fall.

Two of the papers at the core of this thesis collectively demonstrate that CCS and DAC are complementary in structurally distinct ways, which can be characterized as parallel integration and series integration.

Paper II represents parallel integration, whereby a CHP plant simultaneously operates CCS via a PCC unit that is capturing biogenic CO_2 from flue gases and a DAC system that is capturing atmospheric CO_2, with both systems sharing the same heat, electricity, and CO_2 transport infrastructure. In this configuration, CCS and DAC are not substitutes but co-products, with each generating CDR credits from different carbon streams, and their economics being mutually reinforced through shared infrastructure investments.

Paper IV represents series integration, whereby MEA scrubbing captures the bulk of the emissions from high-concentration flue gases and a TVSA polishing step captures the residual fraction, to achieve net-zero direct emissions. Here, CCS and the DAC-derived technology operate sequentially on the same flue gas stream, with the polishing step exploiting the higher CO_2 concentration that becomes available after partial capture. This confers a thermodynamic advantage over atmospheric DAC, which makes the series configuration consistently more cost-effective than stand-alone MEA or MEA with external DAC offset under most conditions.

1.15.2 Other paths of reaching net-zero emissions

Papers III and **IV** compare capture-based pathways solely among carbon capture mitigation methods, excluding alternatives such as electrification and fuel switching.; such as electrification and fuel switching. This is a deliberate choice, as the viability levels of these alternatives vary considerably according to the industry studied and cannot be generalized across the parametric space studied. That said, the carbon avoidance costs derived here can serve as a reference metric against which electrification and fuel switching options may be benchmarked in future work. This is particularly relevant for industries in which the emissions source is not combustion but process-related, with aluminum production being a notable example, where emissions arise from the carbon electrodes themselves. In such cases, the costs derived here provide a meaningful threshold for evaluating bio-based electrode alternatives.

A related observation concerns the roles of biomass and green carbon in reaching net-zero direct emissions in industries. Biomass is a regionally constrained resource, and it is unlikely to be available at the scale required to enable net-zero direct emissions of all industrial processes. However, the finding from **Paper IV** that cost-optimal MEA capture rates approach 97%–99% suggests a potentially important role for fuel switching in a narrow albeit significant window. If fossil fuels are replaced with bio-based alternatives corresponding to the residual 2%–3% of emissions that remain after high-rate capture, net-zero direct emissions become achievable through combining point capture at an optimal capture rate and partial fuel switching to biogenic feedstock. This reframes biomass not as a primary driver of emissions reduction but as a precision instrument for closing the final gap to net-zero emissions, which may be a more-realistic and resource-efficient use of the limited supply.

Conclusions

This thesis systematically investigates the interfaces between CCS, DAC, and DAC-derived technologies, exploring the conditions under which DAC deployment becomes technically feasible and economically viable. The major finding is that CCS and DAC are complementing rather than competing technologies. The deployment of CCS creates the infrastructure, operational experience, and financing conditions that facilitate subsequent DAC deployment, while DAC in turn enables industries to reach net-zero direct emissions beyond what CCS alone can achieve in a cost-effective manner.

RQ I: DAC integration into CHP plants

The integration of sorbent-based DAC into CHP plants equipped with PCC represents a viable direct implementation opportunity, particularly where district heating networks provide access to low temperature heat and where shared CO_2 transport and storage infrastructure with CCS can be developed. At a CDR credit price of 615 €/tCO_2, CDR becomes the dominant revenue stream for such plants, contributing up to 80% of the net cash flow when biogenic capture via PCC is included. The simultaneous retrofitting of PCC and DAC yields substantially lower break-even CDR credit prices than retrofitting DAC into an existing CHP-PCC plant, suggesting that joint investment decisions are highly preferable. Grid-wide implementation across Swedish CHP plants could contribute approximately 33% of the country's national CDR target, highlighting the systemic importance of this deployment pathway. However, feasibility depends critically on access to a CO_2 transport and storage infrastructure, making port-adjacent plants the most-attractive candidates in the near term.

RQ II: DAC-derived technologies for CO_2-lean flue gases

For industries that are emitting CO_2-lean flue gases, the cost-optimal capture technology depends strongly on the plant scale, CO_2 concentration, and the carbon intensity of the local energy supply. In the short term, onsite capture is more cost-effective than purchasing CDR credits only for large-scale sources, such as NGCC plants. For medium-scale sources, such as iron ore pelletization and aluminum production plants, capture costs fall within or just below the current range of CDR credit prices, making the choice sensitive to site-specific conditions and transport and storage costs. For small-scale, low-concentration sources such as silicon production, purchasing CDR credits remains the lower-cost option in the short term, which means that these industries can be classified as economically hard-to-abate under current conditions. In the medium-to-long term, NOAK cost reductions, particularly for TVSA, are projected to expand the range of industries for which point source capture is more economically beneficial than offsetting, making DAC-derived technologies increasingly competitive. Thermodynamically, none of the point source configurations studied can be classified as hard-to-abate relative to the DAC benchmark. This confirms the idea that when designing a carbon capture pathway to reach net zero direct emissions from a specific source, it is recommended that point source capture be prioritized over atmospheric wherever technically feasible.

RQ III: DAC-derived technologies as a "polishing step" for CO_2-rich flue gases

For industries that are emitting CO_2-rich flue gases, the results substantially revise the conventional assumption that DAC offsets approximately 10% of the emissions remaining after 90% CCS capture. With cost-optimal, net-zero configurations, the optimal MEA capture rate is never less than 97%, such that residual emissions are approximately 1%–3% of the total emissions. This 1%–3% residual is more cost-effectively addressed by an onsite TVSA polishing step rather than by atmospheric DAC under most conditions, further limiting the role of CDR in the industrial emission mitigation portfolio. Offsetting via DAC becomes competitive only when the emissions source is linked with high electricity prices or high electricity carbon intensities, and DAC can be sited in regions with access to cheap or clean electricity particularly for sources with CO_2 concentrations below 4%–9%. In the short term, when TVSA polishing is not yet commercially mature, the practical choice is narrowed to stand-alone, high-rate MEA or MEA combined with purchased CDR credits, with the latter providing a financing pathway for early DAC deployment.

Overall, these findings reframe the role of DAC in the mitigation of industrial emissions. Rather than being a stand-alone CDR solution deployed in isolation, DAC and DAC-derived technologies can be deployed as part of an integrated system alongside CCS. They can be co-located with CHP plants to generate CDR credits, applied directly to dilute emissions sources where conventional CCS is uneconomical, or used as a polishing step to close the gap between high-rate CCS and net-zero direct emissions. The competitiveness levels of all these pathways depend on the parallel development of a CO_2 transport and storage infrastructure and the transition of electricity grids towards low carbon electricity, emphasizing that DAC deployment cannot be evaluated in isolation from the broader energy system transition.

Research outlook

The research presented in this thesis opens up several avenues for future investigations spanning technology development, systems integration, geospatial analysis, market assessment, and CO_2 utilization.

At the technology development level, material degradation is identified in Chapter 2 as a critical factor that influences DAC performance. A natural next step is, therefore, the development and integration of material degradation models into process models, which would provide a clearer understanding of long-term technology behaviors under different weather conditions.

Regarding the integration of DAC into CHP plants, in future work the scope could be broadened to include sources of industrial waste heat, thereby expanding the range of viable deployment contexts. In addition, a more-detailed representation of operational aspects, such as scheduling, part-load behavior, and transient operation, would deepen understanding of how such integrations can be managed in practice. Beyond CHP integration, there are new possibilities to integrate DAC technologies (particularly ALK-ABS) with industries (such as cement or pulp and paper manufacturing), where there are possibilities to make use of common process components.

A geospatial analysis of the net removal cost along the full DACCS chain could be conducted, to identify systematically locations that offer opportunities for low-cost CDR via DAC. Such an analysis would involve evaluating different DAC technology configurations and energy sources, alongside geospatially resolved costs for CO_2 transport and storage. When combined with a lifecycle assessment of DAC technologies and cost development of DAC technologies in the future, this would yield a comprehensive picture of the true net removal cost of CDR via DAC, capturing both economic and environmental dimensions.

The conclusions to be drawn from both the current and future cost estimates are highly sensitive to assumed CDR credit prices, introducing considerable uncertainty given that the only existing CDR market remains voluntary and its future structure is still unclear. To address this, a survey targeting potential industrial buyers is planned, with the aim of assessing their willingness to pay for CDR credits in the voluntary market. This would enable more grounded and concrete conclusions to be drawn from the research findings.

Finally, while this thesis has focused exclusively on the capture and geological storage of CO_2, future work could shift the focus towards CO_2 utilization pathways. Expanding the role of DAC within a broader CO_2 utilization framework and, thereby, reducing dependence on fossil fuels and closing carbon balance, may ultimately prove to be of greater long-term importance, and represents a future direction for the field.

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Appendix

Table 1: MEA model parameters for **Paper III** and **Paper IV**.

Parameters	**Paper III**	**Paper IV**	**Unit**
Capture rate	Constant	Variable	%
Equation of state	ELECNRTL+ PR	eNRTL + PR	-
Lean MEA concentration	30	30	Wt%
Lean CO_2 loading	0.3	Variable	mol CO_2/mol MEA
Rich CO_2 loading	Variable	Variable	mol CO_2/mol MEA
Temperature of flue gas to be vented	>70	>70	°C
Heat exchanger ΔT minimum	10	10	°C
Cooler outlet temperature	28.2	28.2	°C
Flue gas			
Temperature	40	35	°C
Pressure	1.01	1.01	bar
Composition	N_2-CO_2-O_2 mixture	N_2-CO_2-O_2 mixture	Dry-basis
CO_2 concentration	0.5–4.0	4–20	mol%
Absorber			
Flow model	Mixed	Mixed	-
Overhead pressure	1.06	1.06	bar
Packings	Sulzer Mellapak 250.X	Sulzer Mellapak 250.X	-
Packing height	21	Variable	m
Column diameter	≤12	≤12	m
Stripper			
Flow model	Mixed	Vplug	-
Overhead pressure	1.3	1.3	bar
Packings	Sulzer Mellapak 250.X	Sulzer Mellapak 250.X	-
Packing height	10	Variable	m
Column diameter	≤12	≤12	m

Table 2: Parameters used to evaluate the environmental trade-offs associated with using 1 MWh of 100 °C heat via different technologies.

Parameter	**Minimum**	**Maximum**
DAC heat demand [MWh/tCO_2]	5.4[73]	11.9[73]
DAC electricity demand [MWh/tCO_2]	0.5[73]	0.7[73]
DAC material degradation [$t_{sorbent}$/tCO_2]	7.5[73]	
Carbon footprint of the sorbent [kg$CO_{2,eq}$/tCO_2]	6[73]	
Heat pump COP	3[120]	5[120]
ORC efficiency [%]	8[121]	10[121]

COP, Coefficient of performance; ORC, organic Rankine cycle.

Table 3: Main sensitivity parameters and their ranges used for estimating the cost of Direct Air Capture.

		Min	**Median**	**Max**
Process contingency [%TDC]	**L-DAC**	30	50	70
	S-DAC	5	10	20
Capacity factor [%]	**L-DAC**	50	70	90
	S-DAC	75	82.5	90
El price [$/MWh]	**L-DAC**	50	105	150
Ng price [$/GJ]	**S-DAC**	5.6	8.7	

Table 4: Costs and scaling factors of the main components of S-DAC.

Component	Cost [M$_{2021}$/tCO$_2$]	Scaling factor	
Air contactor	3.84	1	Based on Sievert et al [45]
Blowers	1.29	0.63	Based on Sievert et al [45]
Vacuum pump 1	0.19	0.63	Based on Sievert et al [45]
Vacuum pump 2	0.1	0.63	Based on Sievert et al [45]
Gas storage baloons	0.01	0.63	Based on Sievert et al [45]
Condensers	0.46	0.63	Based on Sievert et al [45]
Switching valves	6.01	1	Updated in this work as valves increase in number as the scale goes up
Initial sorbent	0.53	1	Based on Sievert et al [45]
Buildings	0.2	0.67	Based on Sievert et al [45]
Compressor	2.71	0.42	Based on Sievert et al [45]
Heat pump	1.18	0.7	Updated in this work average value to consider scaling
Installation	5.07	0.7	Updated in this work average value to consider scaling

Table 5: Costs and scaling factor of the main components of L-DAC.

Component	Cost [M$\$_{2021}$/t$CO_2$]	Scaling factor	
Air Contactor	79.10	1.00	Keith et al reported modular scale up [45]
Pellet Reactor	53.26	1	Keith et al reported modular scale up
Calciner	17.62	0.6	Circulating fluidized bed [122]
Slaker	15.40	0.57	Based on Sievert et al [41]
ASU	32.87	0.67	Based on Sievert et al [41]
Fines Filter	15.20	0.67	Based on Sievert et al [41]
Other Equipment	46.60	0.67	Based on Sievert et al [41]
Buildings	2.16	0.67	Based on Sievert et al [41]
CO_2 compressions train	10.52	0.73	Based on Sievert et al [41]
Steam turbine	6.85	0.42	Based on Sievert et al [41]
Installation	147.67	0.7	Updated in this work average value to consider scaling