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Rolling-out pioneering carbon dioxide capture and transport chains from inland European industrial facilities: a techno-economic, environmental, and regulatory evaluation

Wordcount: 7342 + 2226 Appendix

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Abstract

Large-scale deployment of CO_2 capture, transport, and storage (CCTS) requires the rolling-out of extensive value chains. In this study, we present the development, design, techno-economic, environmental, and regulatory analysis of four pioneering chains that capture and condition CO_2 from existing European industrial plants and their multi-modal transport to selected ports in Northern Europe. The pioneering chains can avoid between 65% and 87% of the industrial emissions, including scope 3, with a cost of CO_2 avoided ranging between 100 and 300 €/tCO_2. The economic and environmental performance of the CCTS chains are substantially affected by the geographic location of the industrial emitters and the CO_2 volumes to be transported.

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1. Introduction

The imperative to address climate change and the rising levels of carbon dioxide (CO_2) in the atmosphere has become increasingly urgent. Carbon dioxide capture, transport, and storage (CCTS) has been identified as a critical component of climate strategies to mitigate emissions [1]. CCTS offers a promising avenue for capturing CO_2 emissions from large point-source emitters, including from hard-to-abate industrial sectors, preventing them from entering the atmosphere, and storing them safely and permanently underground. However, deploying CCTS is a complex endeavour, with multi-faceted technical, economic, environmental, and regulatory challenges that require careful analysis.

In Europe, emitters, particularly those situated in central regions, will face the hurdle of having to transport large amounts of CO_2 (on average 250 ktCO_2/y per emitting plant [2]) most likely to port within the continent for subsequent storage offshore, which is being more extensively developed compared to onshore storage. Pipelines have been identified as the most cost-effective CO_2 onshore transport mode for volumes larger than 2 $MtCO_2/y$ regardless of the transport distance [3]. It is, thus, evident that a cross-border pipeline network will be essential for the transport of substantial CO_2 volumes required to meet European countries' climate objectives. This assertion is supported by a wealth of literature studying the design of CCTS supply chains and networks with a focus on ship and pipeline transport [4–15].

However, the long planning and constructing phases for this pan-European infrastructure pose a significant challenge - particularly considering that planning has only recently started - and will require cross-border cooperation. Moreover, this construction will likely be a phased process, with initial implementation centred around major industrial clusters near CO_2 storage facilities and northern ports. The first pipeline segments might not extend so far to reach larger emission sources located inland, eager to implement CCTS as early movers. Some of these pioneers are already investigating today solutions for CO_2 capture and transport that can be implemented in the near term. Although the range of CO_2 capture and transport technologies commercially available today is limited, there exist off-the-shelf solutions that can be deployed [16].

This contribution focuses on the design of CCTS value chains relying on commercially available CO_2 capture and transport technologies to enable potential implementation within the next two to three years. We consider four large-scale emitters willing and interested in becoming early CCTS movers, situated in diverse European locations, and belonging to hard-to-abate sectors, i.e., waste treatment, pulp-and-paper production, and cement manufacturing [17]. For each emitter, we design CCTS chains to capture and transport

CO_2 from the source to a delivery harbour, from which the CO_2 will be collected by a storage operator. The chains are analyzed based on their techno-economic and environmental performance. Our ultimate objective is to outline a comprehensive set of recommendations for deploying CCTS by early movers, with a specific focus on advantages, disadvantages, and strategies for easing the burden encountered by these pioneers.

The paper is structured as follows: Section 2 describes the four emitters considered in this analysis, and Section 3 presents the methodology adopted. Results are presented in Section 4, and Section 5 presents the lessons learned and general recommendations that can be extrapolated from this work. Section 6 concludes the paper by highlighting the contributions and potential impact of the work.

2. Pioneering chains

In this study, four pioneering chains are developed, designed, and evaluated. The chains are termed "pioneering" as they consider the selected CO_2 emitters as early movers and the CCTS chains as first-of-their-kind. The CO_2 point-source emitters correspond to four existing industrial plants currently advocating the deployment of CCTS as an urgently needed tool to curb their emissions:

- a cement plant from Heidelberg Materials (HM) in Hannover, Germany,
- a cement plant from Heidelberg Materials (HM) in Górażdże, Poland,
- a waste-to-energy (WtE) plant from KVA Linth, in Niederurnen, Switzerland,

• a pulp mill from Stora Enso (SE) in Skutskär, Sweden.

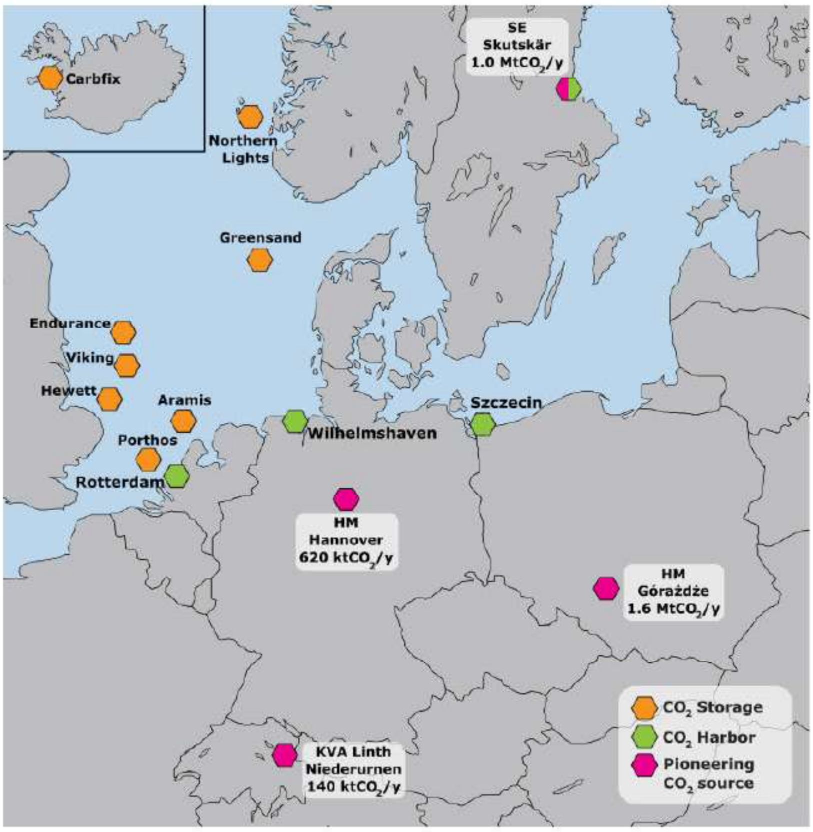

Figure 1: Geographic location of the four emitters considered in the analysis, closest harbours, and commercial CO_2 transport and storage hubs in construction or at an advanced stage of development [18].

These emitters cover a wide spectrum of relevant conditions for deploying CCTS at an industrial scale: (i) they exhibit different flue gas characteristics in terms of volume and composition; (ii) they present case-specific challenges that are representative of several industrial applications, e.g., availability of surplus energy; (iii) finally, their geographical locations introduce sets

Table 1: Main characteristics of the four pioneering chains considered in this study.

	Cement plant Heidelberg Materials	Cement plant Heidelberg Materials	Waste-to-energy plant KVA Linth	Pulp mill Stora Enso
Location	Hannover (DE)	Górażdże (PL)	Niederurnen (CH)	Skutskär (SE)
Total CO_2 emissions [$MtCO_2/y$]	0.69	1.77	0.16	1.10
Biogenic share of CO_2 emission [$MtCO_2/y$]	0.04	0.19	0.08	1.10
CO_2 conc. in flue gas [%]	15%	18%	12%	12%
Distance from harbor [km]	235	450	997	0

of different challenges for transporting the captured CO_2 to the selected delivery harbour. All in all, these four plants offer a comprehensive picture to understand what it takes for the near-term roll-out of CCTS chains from industrial emitters in Europe. In addition, the different degrees of utilisation of bio-resources (leading to different shares of biogenic CO_2 emissions) by the four industries allow for investigating opportunities to deliver carbon dioxide removal (CDR). Table 1 summarises the main characteristics of the four pioneering chains considered in this study, while Fig. 1 illustrates their geographic location, closest harbours, and the potential CO_2 storage site. In the following, we will refer to these four chains simply using their location.

There are several planned and emerging permanent CO_2 transport and storage hubs in Northern Europe[18–24]. Among them, the Northern Lights site in Norway and the Porthos site in the Netherlands are currently the only commercial storage projects under construction with significant capacity and clear expansion plans [19, 21]. In light of the several hubs being developed in Northern Europe, we design in this study pioneering chains to capture, condition, and transport CO_2 to a selected port in Northern Europe using different modes. From the port, it is assumed that CO_2 is transported directly via ship to one of the hubs being developed, although cost and emissions related to this final step are not accounted for in this study. It is essential to be aware of such boundaries when analysing the results. For instance, whenever an emission reduction figure or a cost is reported, these refer to the amount of CO_2 avoided by capturing, conditioning, and transporting CO_2 from the industrial site to the selected port. The transport via ship to the final storage site will result in additional emissions and increased costs. Nonetheless, the decision to focus on the delivery harbor as the final point for the analysis in this study offers a strategic advantage that extends beyond the immediate context of a specific storage site: by choosing the harbor as the endpoint, we ensure that the results obtained can be extrapolated and applied to any storage hubs accessible from the same harbors and currently under development. This choice also acknowledges the potential for collaboration with other stakeholders, such as emitters, transport operators, or storage operators, to optimize transportation from harbors to storage sites by clustering emissions from various sources.

3. Methodology

For the four CCTS chains described in Section 2, CO_2 is captured using a solvent-based absorption process and then conditioned for multi-modal transport in liquid state at 15 barg, as described in Section 3.1. The CO_2 transport options considered are presented in Section 3.2. These first-of-a-kind chains are evaluated using the consistent cost assessment methodology described in Section 3.3. The methodology for accounting of greenhouse gas (GHG) emissions is outlined in Section 3.4.

3.1. Technology for CO_2 capture, conditioning and transport

3.1.1. CO_2 capture and conditioning

CO_2 absorption using aqueous solutions of monoethanolamine (MEA) has been commonly used as the reference technology in benchmark studies of CO_2 capture processes [25, 26]. However, the solvent blend of AMP (amino-methyl-propanol) and PZ (piperazine) has recently been proposed as an alternative benchmark for CO_2 capture processes primarily due to (1) its relatively high maturity, (2) its lower specific reboiler duty for solvent regeneration, and (3) its lower thermal and oxidative degradation compared to other solvents [27]. The solvent AMP has a high absorption capacity but a low reaction rate of CO_2 absorption, which is improved by adding PZ to the AMP solution. The solvent blend of 27 wt. % AMP - 13 wt.% PZ is known as the CESAR1 solvent [28], although the relative content of the two components may vary for different applications. In this study, a 33 wt. % AMP – 12 wt. % PZ solvent composition is used. Such composition was selected based on preliminary analyses where additional compositions (i.e., 27 wt. % – 13 wt. %, and 20 wt. % – 20 wt. %) were tested and compared in terms of energy efficiency at fixed lean loading.

A schematic of the AMP-PZ capture process is shown in Fig. 2, which is very similar to a standard MEA capture process. The flue gas (stream 1) is precooled in a direct contact cooler (DCC) before entering the absorber (stream 4), where the CO_2 is absorbed. A water wash section tops the column to recover solvent from the exhaust gases. In the case of the two cement plants and the pulp-and-paper plant, a second water-wash section is needed to remain within the regulated limits of amine emission to air. While the

CO_2 depleted gas (stream 5) is released to the atmosphere, the CO_2-rich solvent (stream 7) is sent to the stripper. The solvent is heated with steam in a reboiler for regeneration. The purified CO_2 leaves from the top of the stripper (stream 16), while the lean solvent (stream 10) is circulated back to the absorber. A thermal reclaimer is included to purify the solvent and allows for spent solvent disposition. A lean-rich heat exchanger is used for energy recovery. The capture process for the cases considered here has been simulated using Aspen Plus V10. A rate-based modelling approach is used, relying on the unsymmetric electrolyte NRTL property method (ENRTL-RK) [29]. The model is further tuned to represent the behavior of the selected solvent, including properly selected interaction coefficients as well as equilibrium constants and kinetic parameters [3]. The model is validated against experimental data within the range of solvent operating temperatures reported by Brúder et al. [30] (the experimental data reported in Fig. 4 from the referenced paper were considered).

Steam is normally used for regenerating the CO_2-rich solvent. The following options for using biofuels for steam production have been considered: (1) biogas for cement and WtE plants, and (2) biomass for the pulp mill. Those solutions were selected to minimize the additional CO_2 emissions due to steam supply, although their cost is expected to be higher than conventional options, e.g., natural gas-fired boilers. Additionally, the consideration of bio-resources for each location took into account the availability of the specific resource, e.g., the availability of biomass at the pulp mill.

[3]Specific information on the modelling parameters can be made available upon request by contacting the corresponding authors

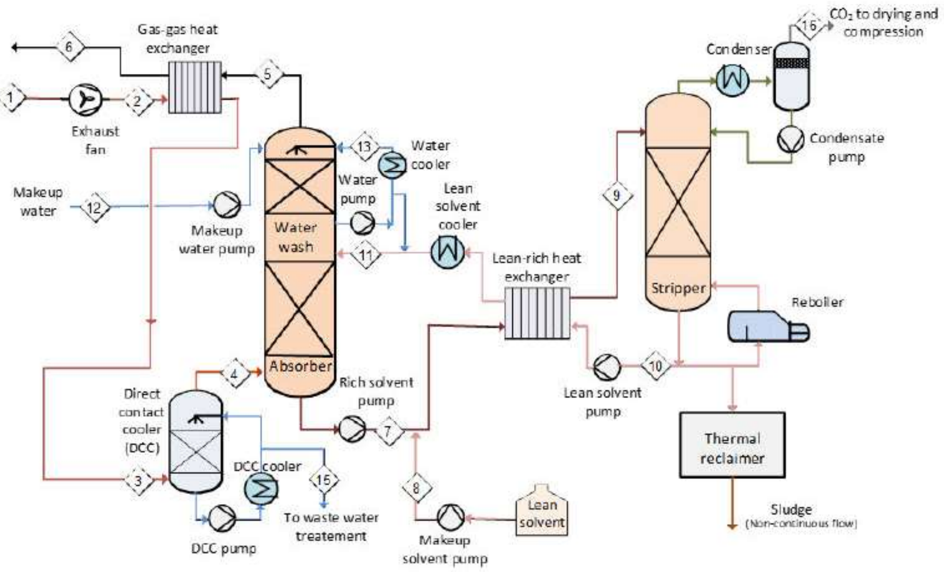

Figure 2: Process flowsheet of the reference CO_2 capture unit. Adapted from [26].

The captured CO_2 needs to be compressed and/or liquefied to the desired conditions depending on the selected transport solution. In this study, liquefaction at a pressure of 15 barg is considered as currently only transport at this pressure is commercially available. A schematic of the CO_2 liquefaction process is shown in Fig. 3, while more information on the conditioning cycle selected can be found in Deng et al. [31]. The process has been studied using rigorous mass and energy balance models developed with Aspen HYSYS V10 for all the relevant process units using property packages and parameters reported by Deng et al. [31]. The SQP-based optimization utility within HYSYS has been used to minimize the overall specific energy consumption of the system considering the following decision variables: (1) the pressure ratios of the various compressor stages, (2) the valve outlet pressures, and (3) the cooler outlet temperatures.

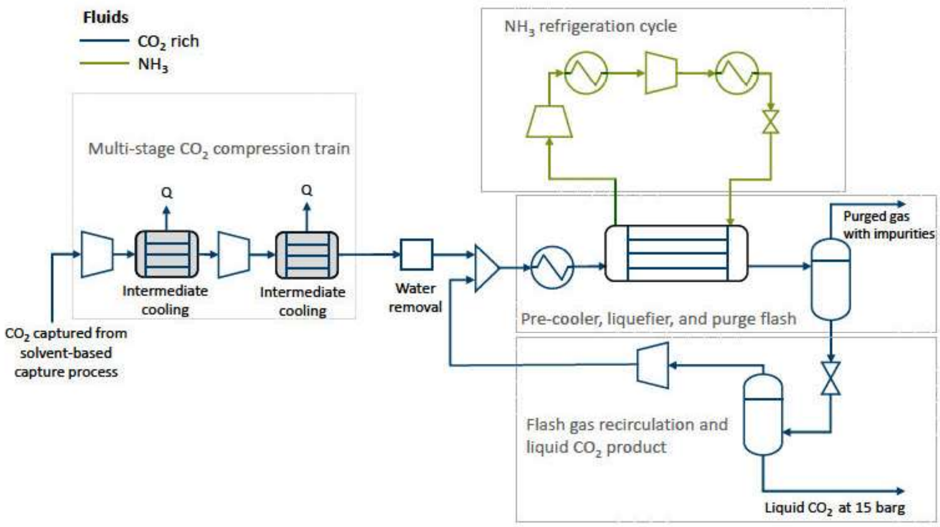

Figure 3: Process flowsheet of the CO_2 liquefaction unit. Adapted from [31].

3.2. CO_2 transport

As this study focuses on pioneering chains, we consider CO_2 transport options that can be implemented in the near term, i.e., mature technologies that do not require any considerable greenfield infrastructure outside of the emitter's site or the receiving harbour. This implies that several solutions are outside the scope of this study, e.g., large intermediate storage facilities and filling stations at exchange sites, the construction of new railway stations, the construction or refurbishment of pipelines, and technologies under development, such as dedicated barges and ships.

All transport options considered in this study carry CO_2 in the liquid state at medium pressure (15 barg and -27 °C at loading). We distinguish between two approaches. First, CO_2 can be loaded into ISO tank containers (typically referred to as isotainers), each holding approximately 20 t CO_2. These isotainers have the same dimensions as typical freight containers and can be loaded onto trucks, trains, barges (on rivers), and ships (on open waters). The CO_2 remains in the container throughout the whole supply chain, and the isotainers are exchanged between transport modes by means of a crane. Second, we consider CO_2 transport relying on fixed tanks installed on dedicated trucks and trains, which generally have a larger capacity than isotainers. More details about the different transport options can be found in Oeuvray et al. [3].

The topology and existing infrastructure at each emitter site are decisive concerning the potential deployment of specific transport solutions. The cement plant in Hannover has a private railway station and can accommodate transport by truck. However, despite being connected to the Stichkanal Misburg, a branch of the Mittellandkanal, there is currently no cargo barge operation from there, and dedicated barge transport is not considered in this study. The situation is similar for the cement plant in Górażdże, which has a private railway station too, but no water connection because the nearby Oder river is not navigable for large vessels. The WtE plant KVA Linth is far from any navigable river, and railway transport is not a viable option (the plant has no private railway station, while the closest freight railway stations do not permit transshipping of CO_2). There is, nonetheless, road access, and the plant is located close to the highway allowing for truck transport. The pulp mill in Skutskär is situated directly by the sea and has a private harbor; therefore, there is no need for transport from the emitter to the harbor.

3.3. *Methodology for cost assessment*

Due to their early mover status, the four pioneering chains are assessed as first-of-their-kind. Consequently, although their cost analysis incorporates typical investment costs, fixed operating costs, and variable operating costs, it is anticipated that the expenses associated with these four pioneering chains will be higher compared to their implementation at a later stage when technologies are more mature and have progressed beyond the early phases of commercialization. To account for these higher costs, this study follows the guidelines developed and described by Roussanaly et al. [32, 33] for cost evaluation of low-carbon technologies. The following sections provide a summary of the assessment, while additional details can be found in Appendix C. The cost evaluations are performed on an EBIDTA (Earnings Before Interest, Taxes, Depreciation, and Amortization) basis and reported for 2020. To reflect the higher financial risk of FOAK, an economic lifetime of 20 years and a discount rate of 10% are assumed.

3.3.1. *Capture and conditioning*

As commonly adopted in literature, a bottom-up approach is used to evaluate the investment cost of the CO_2 capture and conditioning process, whereby the direct cost of each equipment is evaluated using Aspen Process Economic Analyzer. Subsequently, these costs are combined with a set of factors and cost elements to obtain the total capital requirement, as illustrated in Fig. 4. For example, the following aspects are considered to reflect the higher costs of first-of-a-kind applications [32, 33]:

- Increased design margins and material thicknesses to reflect an oversized design and adhere to more stringent design standards;

- Redundant equipment and additional spare equipment allowance to limit the risk of failure and extensive shutdown;
- Higher process contingencies to reflect current low maturity;
- System contingencies to reflect the potential cost associated with the integration of the capture and conditioning units with the industrial plant and site;
- Higher construction period to reflect the delays often observed for projects undertaken for the first time;
- Higher discount rate to reflect the financial risks associated with such projects.

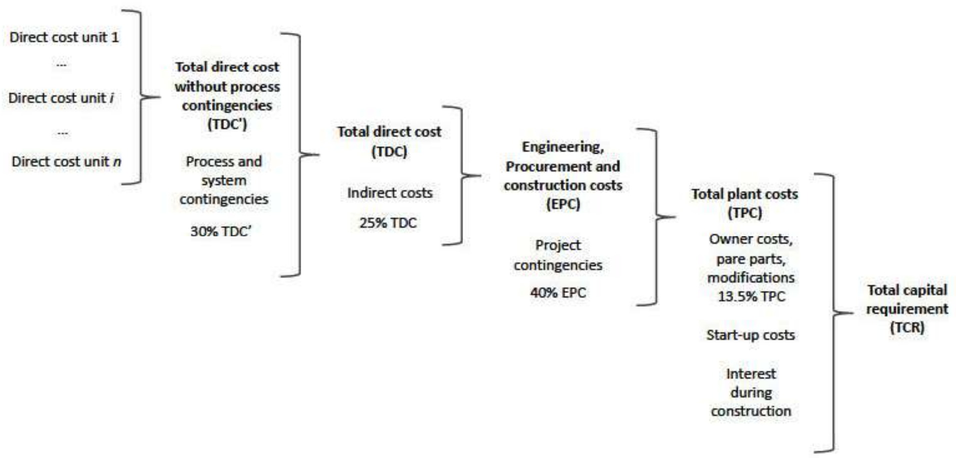

Figure 4: Bottom-up approach for the estimation of the total capital requirement. Modified from [34]

Similarly, while the estimation of the labour, maintenance, and utility costs is based on a commonly adopted approach (outlined in Appendix C), higher costs are also foreseen due to the first-of-a-kind nature of the pioneering chains. Additional labour and maintenance costs are expected in the first years of operation due to e.g., the time required for learning and training, and other inefficiencies. In addition, lower capacity factors are adopted for the first two years of operation, i.e., 40% and 65%. Finally, utility consumption is assumed to be 15% higher than the basis during the first three years of operation [35]. The costs of utilities assumed are reported in Table 2. As electricity costs and carbon intensity differ significantly depending on the location, different values are adopted for each pioneering chain, see Table 3.

Table 2: Costs of utilities used for the techno-economic analysis.

Utility	Unit	Value
Process water [36]	€/m^3	6.65
Cooling water*	€/m^3	0.039
AMP solvent [37]	€$_{2015}$/kg	8
PZ solvent [37]	€$_{2015}$/kg	6
Solvent sludge disposal [38]	€$_{2015}$/t	205
Molecular sieve [39]	€/t	3600
Steam from biomass**	€/GJ	18.2
Steam from biogas***	€/GJ	13.9

*Based on discussion with industrial partners in the project

**Based on a biomass cost of 18 €/MWh

***Based on a biogas cost of 30 €/MWh

Table 3: Electricity costs and carbon intensity for the CO_2 capture and conditioning plants.

Plant	Country	Costs	Intensity	Ref.
HM Hannover	Germany	106.5 €/MWh	521 $kgCO_2/MWh$	[40]
HM Górażdże	Poland	77.5 €/MWh	1047 $kgCO_2/MWh$	[40]
SE Skutskär	Sweden	45.5 €/MWh	46 $kgCO_2/MWh$	[40]
KVA Linth	Switzerland	75.8 CHF/MWh	50 $kgCO_2/MWh$	[41]

3.3.2. Transport

The assessment of the transport costs is based on the methodology described by Oeuvray et al. [3]. The techno-economic assessment considers capital and operational expenditures derived from the transport distance and duration; they include infrastructure, rolling material, labor, maintenance, fuel, insurances and taxes, administrative fees and supplements. The data has been collected directly from industrial and logistics companies whenever possible. Based on the identified transport-exchange terminals and the feasible connections, a network outlining feasible paths leading to a specific harbor is generated for each emitter, as shown in Fig. B.14. This network can be visualized as a directed graph, whereby the nodes represent transport exchange sites where a transport mode exchange can occur, and the edges represent direct connections between two nodes. The weight of each edge is determined by the transportation cost associated with the available transport option for that connection. The Yen's algorithm [42] is used on the simple directed graph to determine the cost-effective routes from a source to a specified harbor.

3.3.3. Cost of CO_2 avoided

The economic performance of the pioneering chains is mainly assessed through the cost of CO_2 avoided (CAC), i.e., the cost to avoid a unit of CO_2 emissions. The CAC is defined as the ratio between the net present value of CCS implementation cost (including capital and operational expenditures) and the discounted amount of CO_2 emissions avoided throughout the years [43]:

$$\mathrm{CAC} = \frac{\mathrm{NPV_{CCS}}}{\sum_i \frac{m_{\mathrm{CO2,avoided},i}}{(1+r)^i}} \tag{1}$$

with $\mathrm{NPV_{CCS}}$ being the net present value of total annual CCS costs (which may vary from year to year), $m_{\mathrm{CO_2,avoided},i}$ the mass of CO_2 avoided by CCS implementation in year i over the full life cycle and r the discount rate.

3.4. Methodology for Life Cycle Assessment

The life cycle assessment (LCA) quantifies the climate change and other environmental impacts of the four pioneering CCTS chains from the CO_2 capture up to the delivery of the CO_2 to the nearest harbour. The LCA system boundary includes all emissions of the CCTS chains while excluding the point source itself (see Fig. 5). The processes in the system boundaries are grouped into three sub-systems: Scope 1, Scope 2, and Scope 3 emissions, following the definitions of the greenhouse gas (GHG) protocol [44]. Scope 2 emissions include the whole life cycle of the electricity generation, while Scope 3 emissions include all indirect emissions from up- and downstream processes. Upstream processes can be the production of steel and concrete for construction, while downstream emissions occur, for example, in the treatment of waste streams.

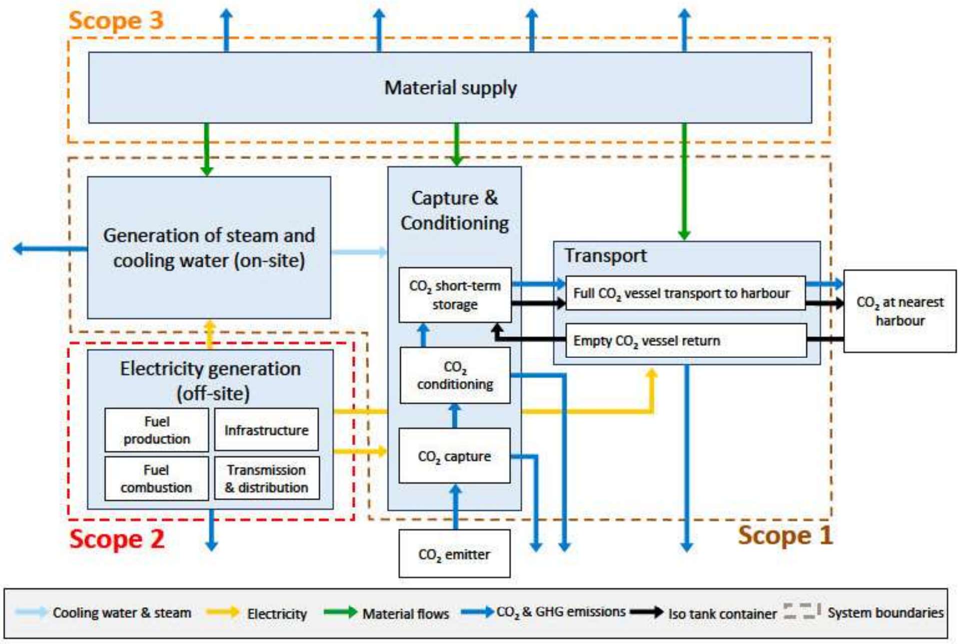

Figure 5: System boundary of the LCA divided into Scope 1, Scope 2, and Scope 3 emissions.

The LCA is based on the work of Burger et al. [45] and follows the methodology defined in ISO 14040:2021 and ISO 14044:2021 [46, 47]. The global warming impact (GWI) of the pioneering chains is assessed using the global warming potential over a 100-year time horizon from the "Environmental Footprint" version 3.0 impact assessment methods [48]. All impacts are scaled on a functional unit, which is the product or service delivered by the plant. Therefore, the functional unit is one ton of clinker ($t_{clinker}$) for both cement plants, one ton of incinerated municipal solid waste (t_{waste}) for the WtE plant, and one air-dried ton of pulp (adt_{pulp}) for the pulp mill.

By quantifying the chain's GHG emissions, the LCA shows the potential for (i) the amount of avoided CO_2 and (ii) the amount of CDR to be generated:

$$m_{CO_2,\text{avoided}} = m_{CO_2,\text{em w/o CCTS}} - m_{CO_2,\text{em w/ CCTS}} - CC_{\text{chain}} \quad (2)$$

with $m_{CO_2,\text{avoided}}$ being the avoided CO_2 emissions, CC_{chain} the climate change impact of the chain (i.e., the direct and indirect emissions caused by the implementation of the CCTS chain), $m_{CO_2,\text{em w/o CCTS}}$ the amount of CO_2 emissions prior to implementing CCTS, and $m_{CO_2,\text{em w/ CCTS}}$ the amount of CO_2 emissions still being released after the implementation of CCTS. The CDR potential of the CCTS chains is linked to the biogenic fraction of the plant emissions and is defined as:

$$m_{CO_2,\text{CDR}} = m_{CO_2,\text{bio, em w/o CCTS}} - m_{CO_2,\text{em w/ CCTS}} - CC_{\text{chain}} \quad (3)$$

where $m_{CO_2,\text{bio, em w/o CCTS}}$ is the amount of biogenic CO_2 emissions released by the plant to the atmosphere prior to implementing CCTS.

As the system boundary ends at the nearest harbour (see Fig. 5), it excludes maritime transport to the storage site and the subsequent geological storage. Both steps cause GHG emissions that must be included to quantify the overall avoided CO_2 from the point source. Consequently, the presented LCA quantifies the potential of the CCTS chains for CO_2 avoidance and for delivering CDR, focusing on capture and inland transport, which have the largest environmental impact [45]. For example, an LCA of the maritime CO_2 transport and offshore storage at the Northern Lights storage site estimates life cycle emissions of 2.6 % for the total amount of CO_2 injected [49]. The influence of these steps of the CCTS chain on the overall CO_2 avoidance potential is expected to be limited.

While the goal of CCTS chains is the reduction of global warming intensity of the industrial point source, CCTS chains unavoidably lead to other environmental impacts. Thus, we analyse fifteen additional environmental impact categories besides GWI to quantify the extent of burden-shifting. The results for all environmental impact categories are reported in Appendix A.

4. Results

4.1. CCTS chains designs

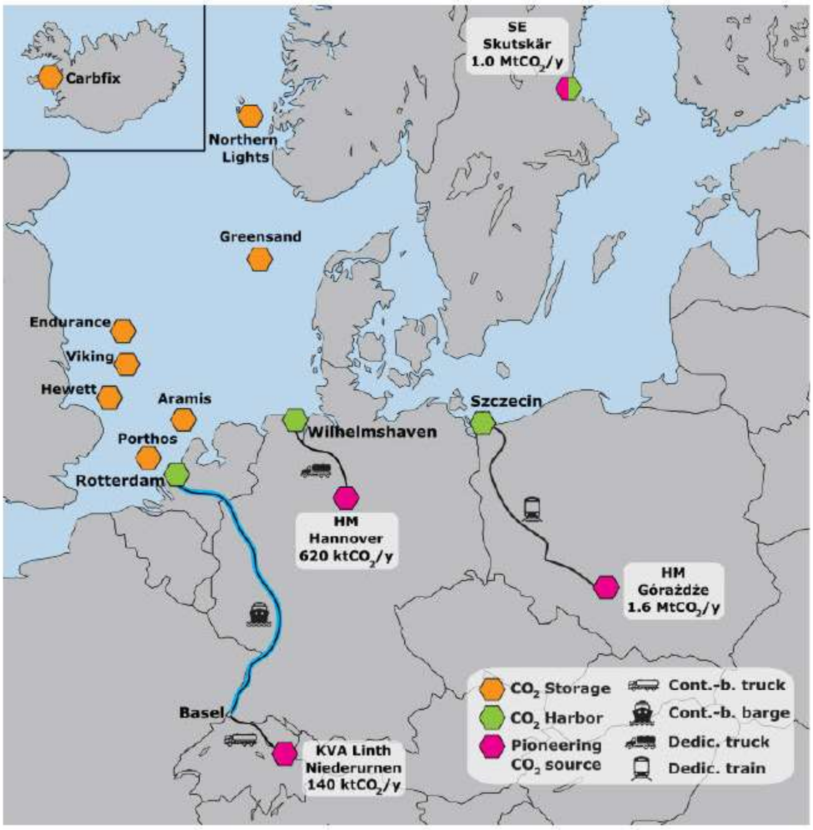

Figure 6: Illustration of the pioneering chains from the four emitters to the closest harbours.

Table 4: CO_2 emissions and avoidance values for the pioneering chains. CCR stands for CO_2 capture rate (higher than 89% in all cases as a result of a 90% CO_2 captured from the capture unit and of a minor CO_2 loss in the conditioning unit).

		CO_2 emissions w/o CCTS (biogenic/fossil)	CO_2 emissions captured	Scope 1, 2 and 3 CO_2 emissions due to CCTS	CO_2 avoided w/ CCTS (reduction/removal)
Hannover	$\frac{kg_{CO_2}}{t_{clinker}}$	868 (52/816)	777	129	648 (648/0)
Górażdże	$\frac{kg_{CO_2}}{t_{clinker}}$	884 (97/786)	790	221	570 (570/0)
Niederurnen	$\frac{kg_{CO_2}}{t_{waste}}$	1241 (645/596)	1113	188	925 (596/330)
Skutskär	$\frac{kg_{CO_2}}{t_{adt_{pulp}}}$	2041 (2041/0)	1837	57	1780 (0/1780)

The transport configurations selected for the pioneering chains are shown on a map of Central/Northern Europe in Fig. 6. In detail, the cement plant in Hannover, Germany, is connected with the harbour of Wilhelmshaven by dedicated road transport. Trucks effectuate daily roundtrips on the 235 km-long connection to transport the captured CO_2 from the cement plant to the harbour. The cement plant in Górażdże, Poland, is connected via railway to the harbour of Szczecin, located 450 km apart. Five trains composed of dedicated wagons convey the CO_2 daily. The total distance travelled is longer for the CO_2 captured at the WtE plant in Niederurnen, located in Switzerland, a land-locked country. In this case, the CO_2 is loaded into isotainers, which are transported first by truck to Basel and then by barge, over the 1000 km from Niederurnen to the Rotterdam harbour. Finally, due to its coastal location and infrastructure, the pulp mill in Skutskär, Sweden, has direct access to a suitable port.

4.2. CO_2 emissions accounting and avoidance potential

Fig. 7 shows the CO_2 emissions breakdown for the four pioneering chains in terms of specific CO_2 emissions, defined as the amount of direct and

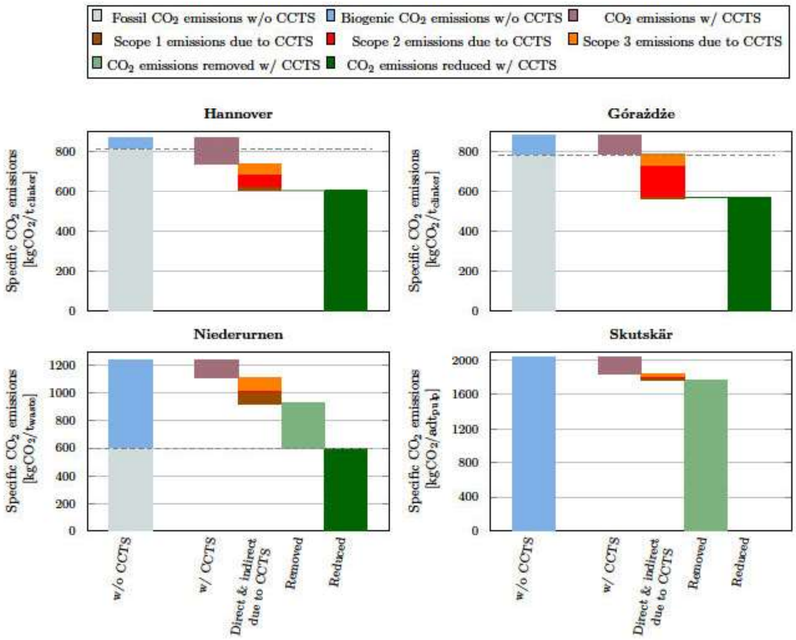

Figure 7: Breakdown of CO_2 emissions without and with CCTS: Fossil (gray) and biogenic (blue) emissions prior to the implementation of CCTS; CO_2 emissions (purple) still remaining after the implementation of CCTS (i.e., due to the limited CO_2 capture rate; indirect emissions caused by CCTS divided into scope 1 (brown), 2 (red) and 3 (orange); CO_2 emissions removed (light green) thanks to the implementation of CCTS; CO_2 emissions reduced thanks to the implementation of CCTS.

indirect CO_2 emissions per unit of industrial product, with and without the implementation of CCTS. Table 4 reports the related emissions and avoidance values. Without CCTS, each plant is responsible for a given amount of CO_2 emissions depending on the industrial process, divided into fossil (gray bar) and biogenic (blue bar) emissions. For example, the biogenic CO_2 fraction of the emissions from the Hannover cement plant corresponds to 6% (52 of the total 816 $kgCO_2/t_{clinker}$), while for the Skutskär pulp mill the fraction is 100%.

The implementation of CCTS implies that a large amount of the industrial CO_2 emissions is captured and conditioned on-site to be made ready for transport. The share of CO_2 emissions that is captured is defined by the CO_2 capture rate (CCR). The CCR corresponds to 90% for all the capture plants, a value that is slightly reduced due to CO_2 losses in the conditioning process (the actual CCR is above 89% for all chains). Therefore, ca. 11% of the CO_2 produced by the plant is still being emitted after the implementation of CCTS (purple bar). Note that a CCR of 90% for the capture process was arbitrarily selected for consistent comparison among the CCTS chains, despite the fact that higher CCR are feasible and the optimal CCR is likely case specific [50]. Upon implementation of the CO_2 supply chain, direct and indirect emissions (scope 1, 2, and 3) occur and must be accounted for (stacked bars – each scope is represented with a different colour, i.e., orange, red, brown). These additional emissions reduce the potential for CO_2 avoidance (reduction and/or removal).

The amount of CO_2 avoided can be obtained as the difference between the total CO_2 emitted to the atmosphere without CCTS and the CO_2 emitted after its implementation; the latter stems either at the plant because the CO_2 capture rate is less than 100%, or directly and indirectly along the CO_2 chain. The CO_2 avoided term comprises both CO_2 emissions removed (light green bar) and CO_2 emissions reduced (dark green bar). The relative share depends on the fossil and biogenic content, respectively, of the total CO_2 emissions, in accordance with the principles outlined in Section 3.4. The CO_2 reduction expresses the decrease of net fossil CO_2 emissions released into the atmosphere with respect to the plant without CCTS. The CO_2 removal implies that there is also a net removal of CO_2 from the atmosphere due to the implementation of CCTS, meaning that the CO_2 uptake of the biogenic source is larger than the overall CO_2 emissions to atmosphere. In other words, CO_2 removal takes place when a positive difference between the amount of biogenic CO_2 emissions without CCTS on one hand, and the total CO_2 emissions with CCTS, including uncaptured as well as direct and indirect emissions due to CCTS, on the other hand, is achieved. For example, the pulp mill uses primarily bio-resources in its industrial process, while the WtE plant considered here processes a large fraction of biogenic waste. Thus, the implementation of CCTS at these two plants results in a large CO_2 removal potential. Conversely, the cement plants, at today's conditions, although reaching significant CO_2 reduction, do not yield CO_2 removal.

Based on the emissions accounting described, the pioneering chains exhibit a potential to avoid 65% to 87% of their emissions. The residual emissions are due to the capture process (i.e., the CCR is lower than 100%) and to the energy needs for implementing CCTS, which causes direct (scope 1) and indirect (scope 2 and 3) CO_2 emissions.

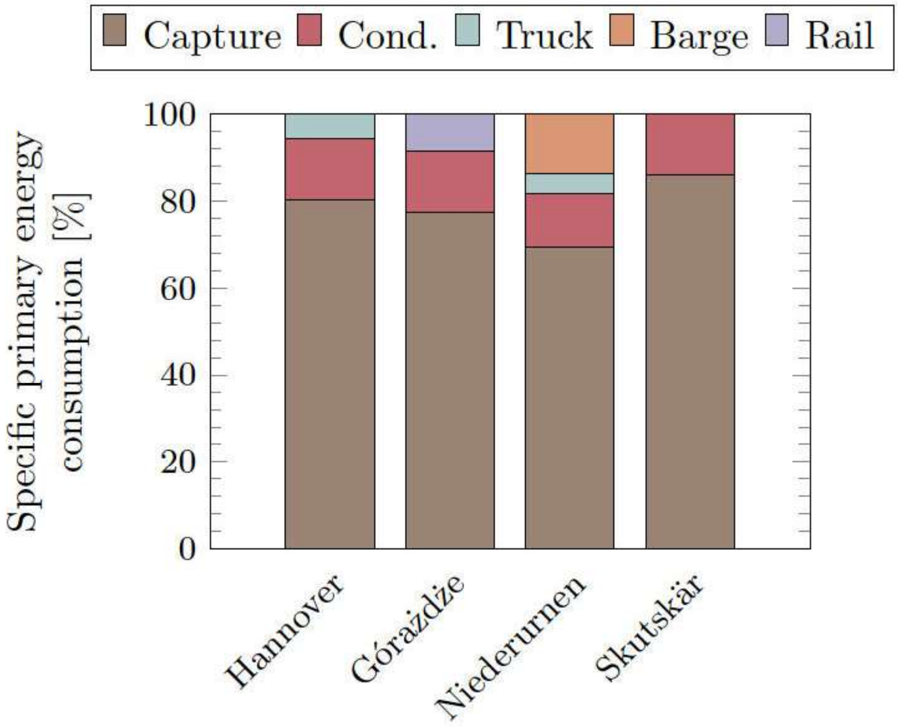

Figure 8: Breakdown of the specific energy consumption with respect to the elements of the pioneering chains. The total specific primary energy consumption for each chain corresponds to 3473 $MJ/t_{clinker}$ and 3477 $MJ/t_{clinker}$ for the cement plants in Hannover and Górażdże, respectively; 5568 MJ/t_{waste} for the WtE plant; and 7938 MJ/adt_{pulp} for the pulp mill.

The relative breakdown of the specific primary energy consumption with respect to the chain elements is presented in Fig. 8, while the absolute numbers are reported in the caption. The main energy inputs are power and heat for the capture and conditioning processes, as well as fuels (i.e., trucks and barges) or electricity (i.e., trains) for the means of transportation. The capture process is by far the main contributor to the energy consumption for all the chains. Energy-wise, transport plays a significant role for the chains located far from a harbour (e.g., 18% for the Niederurnen chain).

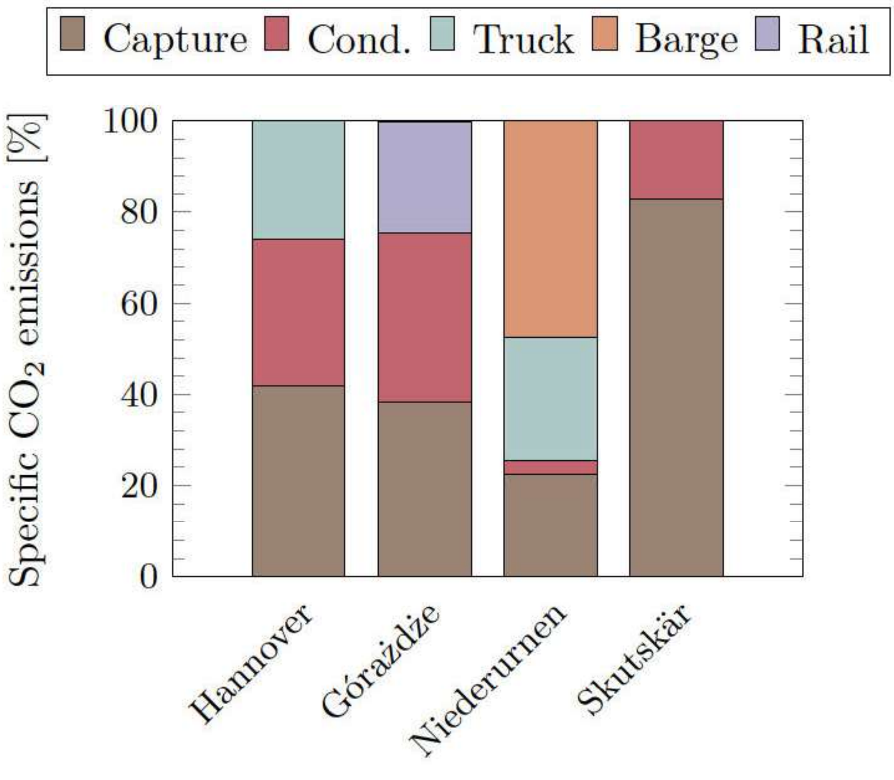

Figure 9: Breakdown of the specific CO_2 emissions with respect to the elements of the pioneering chains.

The breakdown of the specific CO_2 emissions with respect to the chain elements is presented in Fig. 9. Although the energy requirement for capture is dominant regardless of the chain, its impact on environmental performance is more limited. This is due to the utilization of biofuels such as biogas and biomass to produce steam for the capture process. Conversely, despite having a smaller energy requirement, power-driven processes, such as CO_2 liquefaction, may have a significant carbon footprint depending on the carbon intensity of the electricity mix. The two cement plant chains, for instance, source electricity from national grid mixes that still rely heavily on fossil fuels.

Overall, the most impactful factors on the GHG emissions results are: (1) the types of fuels used and their associated CO_2 intensity, (2) the CO_2 intensity of the electricity grid mix, and (3) the length of the transport route from source to harbour, whereby the geographic location of the emitting industrial plants affects the grid mix and the transport route significantly.

4.3. Economics of the CCTS chains

The large impact of geographic location is also revealed by the analysis of the economic performance of the pioneering chains. Fig. 10 shows both the breakdown of the cost of CO_2 avoided with respect to chain elements and cost terms. The capture plant is, on average, the dominant factor. Similarly to the energy and emissions figures, the transport cost becomes relevant in certain cases (e.g., the Niederurnen chain) depending on the location of the industrial plant. A long distance to the nearest port requires the design of a complex, extensive, and expensive transport route. Vice versa, the proximity to a port obviously allows to reduce the cost of CO_2 transport. In addition, an industrial site located in a favourable position, such as along a navigable

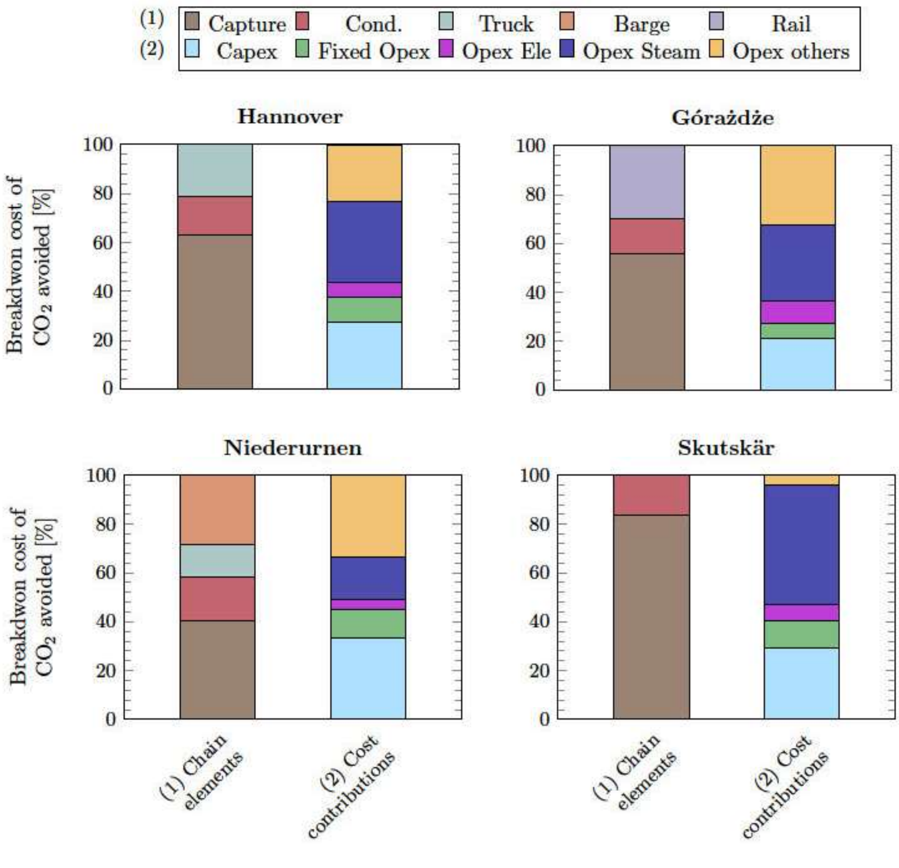

Figure 10: Breakdown of the cost of CO_2 avoided of the pioneering chains with respect to (1) chain elements (left bar) and (2) cost terms (right bar).

river, leads to lower transport costs. The geographical location also affects the cost of the energy sources (primarily the cost of electricity) and their carbon footprint. An example of a pioneering chain benefiting from a favourable geographic location is the pulp mill chain. The pulp mill is located on the coast (indeed, no transport costs are included) and in a country (i.e., Sweden) characterized by relatively inexpensive and clean electricity. The WtE plant in Switzerland offers a different example: it can make use of relatively clean electricity locally, but it faces major energy and cost burdens because of the need to transport the CO_2 to the port of Rotterdam, i.e., through a fairly long transport route, along which fossil fuels play still a major role.

Other factors that significantly impact the costs are the scale and the characteristics of the industrial flue gas to treat: larger scales lead to smaller specific costs of the capture and conditioning units, at least with the technologies considered. For instance, the scale contributes to a cost gap of ca. 50 €/t CO_2 for capture and conditioning between the largest industrial installation (i.e., the Górażdże cement plant) and the smallest one (i.e., the WtE plant). Potentially, the characteristics of the flue gas can have an impact too, especially in terms of CO_2 concentration. However, the range of concentrations of the four industrial flue gases considered, i.e., between 12% and 20% in volume, yields differences in cost of capture, which are possibly below the intrinsic uncertainty we have in determining the costs of the entire chain [51].

Concerning the contribution of various cost terms, the OPEX is normally the major component, when all its terms are summed together. Among those, the variable OPEX related to steam production (i.e., OPEX Steam) and the variable OPEX "others" (a term that includes non-energy related costs such as the cost of chemicals and the costs incurred in operating the transport logistics) are the two largest costs, although the latter, being mainly related to transport, is more case-specific. CAPEX is consistently a substantial share (15-30%) of the overall CAC, irrespective of the industrial case.

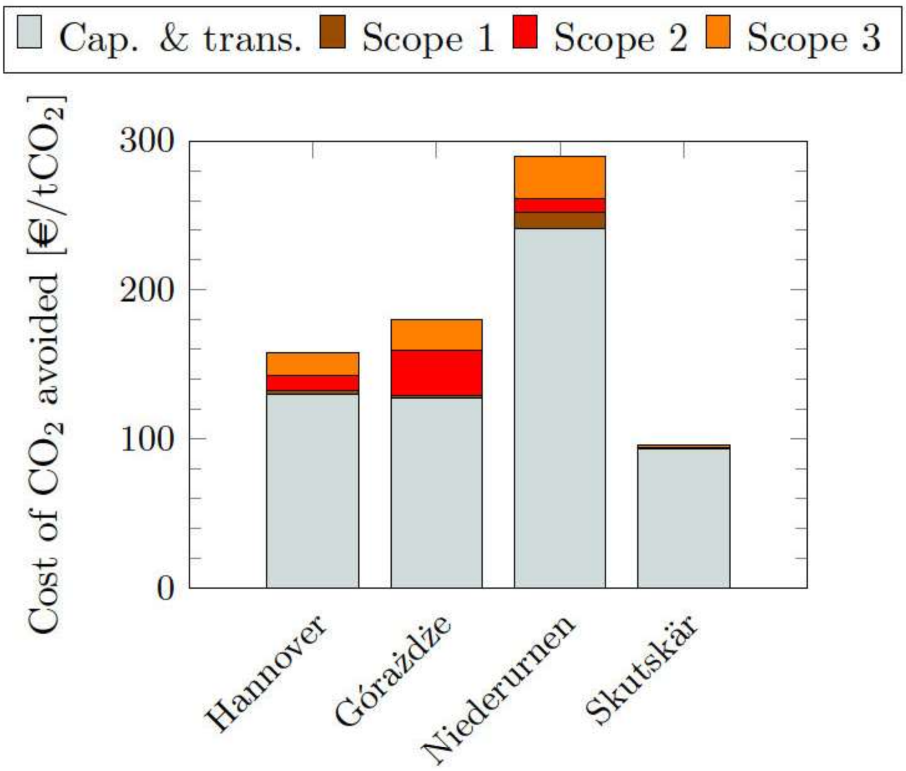

Figure 11: Cost of CO_2 avoided (CAC) of the pioneering chains and effect of different boundaries of the direct and indirect emissions considered. Capture and transport cost (grey bars) does not account for the direct and indirect emissions along the chain. The effect of the direct and indirect emissions (scope 1, 2 and 3) on decreasing the CO_2 avoidance, ergo increasing the CAC, can be noted added on top (brown, red and orange bars, respectively).

All the factors described combine to determine the CAC of the pioneering chains. The CAC achieved is shown in Fig. 11, including the effect of different boundaries of indirect emissions considered (i.e., scope 1, 2 and 3). The pioneering chains exhibit a CAC between 100 and 300 €/t CO_2.

The effect of the additional emissions may be significant – e.g., the final cost figure is increased by 40% in the case of Górażdże. The impact of designing a complex value chain can also be noted, for instance, by comparing the results for Niederurnen and Skutskär. The need for long transport routes, as is the case for industrial emitters located in inland Europe, implies significant costs for operating the transport logistics (a key factor explaining the difference between the grey bars), and direct and indirect emissions along the chain (particularly scope 1 and 2 emissions, in brown and red in the figure). Increased costs and emissions lead to higher CAC values.

5. Discussion and learnings

5.1. Cost of full-scale demo capture facilities

A distinctive aspect of the cost evaluation presented in this study for the pioneering chains is that it is performed on a FOAK basis, as explained in Section 3.3, to reflect the higher cost typically associated with such early movers. Considering the very limited number of such assessments performed in literature for CCTS value chains, it is interesting to understand how such an evaluation compares to a Nth-of-a-kind (NOAK) evaluation (as commonly performed in literature[4]) and the main contributions to the increase in FOAK

[4]This means a "what-if" type of NOAK evaluations, describing the "aspirational NOAK cost" that is obtained if cost and performance targets are successfully met. Conversely, a "what-will" type of NOAK evaluations describe the "expected NOAK cost" or "projected

costs with respect to NOAK. To this end, the costs of capture and conditioning for the Skutskär chain were evaluated also on a NOAK basis. The NOAK approach resulted in a cost of 71 €/t CO_2 for capture and conditioning compared to 93 €/t CO_2 for the FOAK case, which thus yields 30% higher costs, all other things being equal. Figure 12 shows the breakdown of the capture cost using both FOAK and NOAK approaches. CAPEX is, as expected, more impacted[5] than fixed or variable OPEX. The cost difference is mainly[6] attributed to the bottom-up factors used (Table C.7 in Appendix C provides an overview of the main factors used for FOAK and NOAK evaluations). In addition, the level of equipment redundancy contributes significantly to this cost gap.

The adoption of FOAK approach provides valuable insights into the heightened costs involved in the capture and conditioning of CO_2 anticipated for early deployment. It is imperative to acknowledge that these costs are poised to decrease as additional facilities are commissioned and technological advancements occur[7]. For instance, potential sources of this cost reduction

NOAK cost" that will likely be reached by a technology at a point in time. More insights are presented in Roussanaly et al. [33].

[5]The total capital requirement (TCR), Fixed OPEX and Variable OPEX contributions (in €/t CO_2) to CO_2 capture cost are 133, 62, and 3%, respectively, in the FOAK than the NOAK.

[6]The FOAK cost methodology leads to TCR (in M€) 93% than in the NOAK, which in turn also increases fixed OPEX. However, other elements such as the shorter project duration, the discount rate, and the assumed lower efficiencies in the first couple of years also play a role in the higher cost observed in the FOAK case.

[7]As higlighted by Roussanaly et al. it is important to note that "what-if" NOAK estimates are not expected to evaluate the actual cost of a plant post-demonstration i.e.

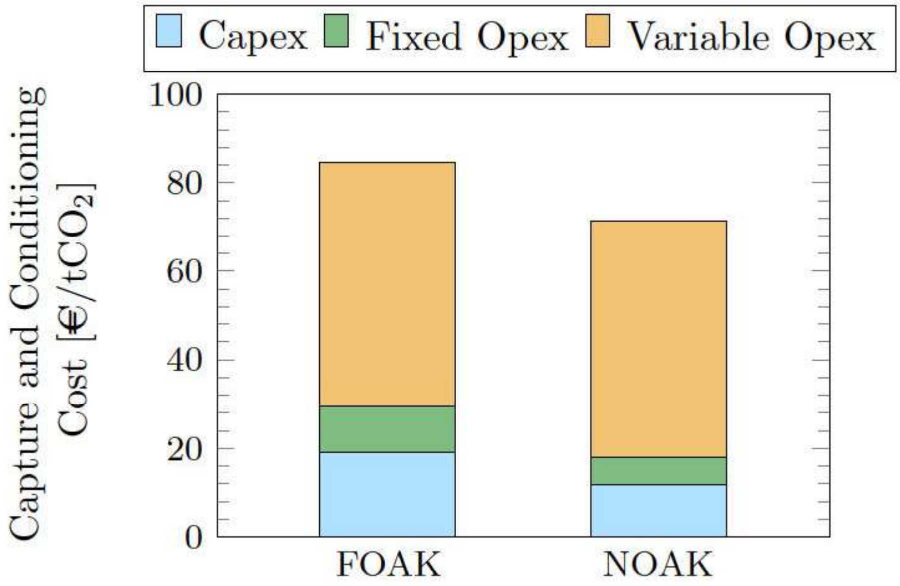

Figure 12: Comparison of FOAK vs. NOAK capture and conditioning cost for the Skutskär pioneering chain.

may include:

- As observed for most new technologies, investment and operating costs tend to decrease with increase capacity deployment thanks to learning-by-doing and research. This is typically owed to process modifications and improvements based on practical experience, reduced need for redundancies and over-design, more reliable integration with the plant, modularization, standardization, etc. Such effects are already observed for CCS applications at coal-based power plants [52].

- The cost-effectiveness of energy supply, particularly in absorption-based CO_2 capture, hinges significantly on the steam cost for solvent regeneration (as shown in Fig. 10). In this study, we assumed steam to be generated via biogas and biomass combustion to mitigate potential challenges in heat recovery and integration with the industrial plant under consideration, and, in the WtE case, to maintain the same power output. However, such methods incur substantial costs (and greenhouse gas emissions if reliant on fossil fuels). A proven approach to alleviate these expenses involves recovering surplus heat from the industrial plant or nearby facilities to produce steam [53]. Depending on the specifics of each case, this may vary in complexity, ranging from direct steam extraction of sufficient quality to the recovery of low-quality steam necessitating further enhancement through methods like heat pumps.

once technology is mature. For that a "what-will" type of NOAK estimates would be more appropriate. A "what-will" type of NOAK estimates must be derived from FOAK estimates through learning rates and other aspects [33].

5.2. Cost of transport for early movers located in inland Europe

The costs of transport associated with the supply chains of the emitters considered in this study are shown in Fig. 10. The associated transport pathways can differ in cost, roundtrip duration, required logistics, and operational-to-capital expenditures ratio. It is worth noting that the costs of transport reflect mainly the distance, because the existing transport options are modular and thus offer limited economies of scale. As empirical guideline for inland transportation costs with pioneering options based on the chains evaluated in this work, the cost from emitter to harbor scales linearly with distance, with a unitary cost of ca. 1 €/tCO_2 transported over 10 km.

Transport technologies such as dedicated transport and pipelines are more efficient than container-based transport, although they require more infrastructure and thus a longer lead time [3]. Furthermore, they offer economies of scale. As the amounts of CO_2 transported will grow, the transport costs are expected to decrease by 50-75% over the entire supply chain [3]. Pipeline networks are planned to connect coastal regions with industrial regions, and thus allow for an economical and continuous delivery of captured CO_2 [21, 54].

5.3. Supporting the burden of early movers and valuing CDR

As highlighted in the earlier sections, the CO_2 avoidance cost from capture to the harbour of the four considered pioneering chains varies between 100 and 300 €/t$CO_{2,\text{avoided}}$. The costs of CO_2 transport from the harbour to the storage hub and of CO_2 storage will likely add at least several tens of €/t$CO_{2,\text{avoided}}$. For reference, these costs are significantly higher than the current CO_2 emissions price under the European Union's Emissions Trading

System (EU ETS), thus making CCTS deployment from the facilities under the EU ETS not economically viable today.

A significant challenge for the four CCTS chains analyzed here is the higher costs incurred as early movers, which might result in the decision to delay implementation. To overcome this key challenge to implementation, several possibilities could be explored [55].

Support to partly cover the burden of the investment costs could be sought at the national or European Union level [55]. Such measures include contributions to up-front costs, grants to cover engineering studies, e.g., Front End Engineering Design (FEED), loan support (enabling preferential interest rates, access to debt capital, and loan guarantees), and tax credits. A similar strategy could be seeking national or EU-level operational subsidies to create predictable revenue streams [55]. This could be achieved through, e.g., tax credits and/or contracts-for-difference.

Another opportunity for some of these CCTS chains is to create the largest value from the generated CDR. As highlighted in Fig. 7, two of the chains considered here can generate significant levels of CDR through the capture and permanent storage of biogenic CO_2 produced by these facilities. Indeed, high-quality CDR in voluntary carbon markets or private financial agreements are valued at prices as high as 700 $/t$CO_2$ [56, 57]. Let us consider the case of the WtE plant located in Niederurnen, Switzerland. Without any revenue from selling the generated CDR, the plant faces a cost of CO_2 avoided for its fossil emissions of 450 €/t$CO_{2,\text{avoided}}$[8]. A revenue of 400 €/t CDR would

[8]This value assumes that the entire economic burden for the implementation of the CCTS chain is allocated to the fossil emissions, which are roughly 65% of the total emissions.

roughly half the cost of CO_2 avoided; if such revenue increased to 750 €/t CDR, the cost would be reduced by more than 90%. While this aspect could present significant opportunities for CCTS implementations that could enable CDR, it is important to note that further work and proper regulations are required to develop suitable business models and prevent double accounting.

Finally, another possibility consists in passing down the additional costs due to the implementation of CCTS to the end-users of the relevant products. Indeed, as highlighted by recent studies [58, 59], a high CO_2 avoidance cost does not necessarily result in a significant cost increase for the end-users of the final products derived from these industrial plants. The end-users could easily absorb this cost increase if the proper mechanisms are in place.

5.4. International and European Regulatory Framework for CCTS

While CCTS has reached technical readiness for implementation, the legal and regulatory framework essential for its effective large-scale deployment and oversight still needs revision and updating.

The International and European regulatory framework is working to enable the implementation and deployment of CCTS technologies through global agreements and national legislation. International law serves as the cornerstone for CCTS activities, emphasizing the importance of responsible practices and cross-border cooperation. Key international agreements, such as the the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and the London Protocol, are instrumental in shaping the regulatory landscape for CCTS, particularly regarding protecting the marine environment and permanent CO_2 storage beneath the seabed.

The EU regulatory framework for CCTS revolves around critical components, notably the EU ETS and the CO_2 Storage Directive. The integration of CCTS into the EU ETS is crucial, given that this legislation forms the cornerstone for reducing greenhouse gas emissions across various sectors. The CO_2 Storage Directive establishes a comprehensive regulatory framework within the EU, addressing key elements such as cross-border transport of CO_2 for storage, third-party access to CO_2 transport networks, qualitative standards for CO_2 purity, and the issue of long-term liability.

In light of these advancements, it is crucial to recognize that, despite the technical readiness of CCTS, legal questions and challenges must be effectively addressed for the large-scale and successful implementation of these technologies [60].

6. Conclusions

This article present the development, design, and techno-economic, environmental, and regulatory analysis of four CCTS pioneering chains, originating from four industrial sites, i.e., two cement plants from Heidelberg Materials (Hannover, Germany, and Górażdże, Poland), a waste-to-energy plant from KVA Linth (Niederurnen, Switzerland), and a pulp mill from Stora Enso (Skutskär, Sweden). The pioneering chains include CO_2 capture and conditioning from the flue gases at the industrial site, and transport to the closest suitable port for further ocean shipment to a permanent storage site in Northern Europe, e.g., the Northern Lights or the Porthos storage site. The transport to the final storage location and the storage itself are not included in the boundaries of the analysis. The industrial sites are considered as early movers, and in view of their pioneering effort, only technological solutions currently available are considered for the design of the chains. In addition, the techno-economic framework considers first-of-a-kind (FOAK) cost estimates.

The pioneering chains achieve a CO_2 avoidance between 65% (Górażdże) and 87% (Skutskär) of their industrial emissions. Although all pioneering CCTS chains can avoid emissions, under this work's assumptions, only Niederurnen and Skutskär have the potential to deliver CDR. The 90% capture rate assumed for the capture process is the main contributor to residual emissions. In addition, direct and indirect emissions also occur along the CCTS chain. The direct emissions are related to the combustion of fuel (CO_2 transport is the main responsible), while the indirect emissions are mostly due to the carbon footprint of electricity. The amount of those emissions is affected by factors such as the length of the transport route and the CO_2 intensity of the energy inputs.

The estimated cost of CO_2 avoided of the pioneering chains lies between 100 and 300 €/tCO_2. The main driver for this variability is the geographic location, which in turn affects the length and complexity of the transport route and the availability of clean and affordable energy. Scale is another important factor, where larger plants can benefit, to some degree, from economy of scale for certain units (e.g., capture and conditioning) compared to smaller ones. The capture plant is, on average, the largest cost share, while the contribution of transport varies extremely depending on the geographical location.

The rollout of the pioneering CCTS chains is characterized by higher costs than typically observed in the literature, due to the additional costs that arise during the demonstration phase of a technology. Assuming that several additional CCTS chains will develop in the future, the maturation of CCTS technologies and infrastructure is expected to result in significant cost reduction (transition from FOAK to NOAK showed to bear expected cost savings larger than 30% for capture and conditioning), as typically observed in new technologies and as already observed in the case of CCS in the power sector. Still, the associated economic penalty must not translate into delayed implementation. Therefore, options should be explored to support the burden of early movers. Targeted policies, e.g., the Carbon Border Adjustment Mechanism, and subsidies schemes are critical. Furthermore, a predictable framework to value CDR can also become essential for those chains that can deliver CDR.

CRediT authorship contribution statement

V. B. Conceptualization, Methodology, Visualization, Writing – original draft, Writing – Review & Editing, Project administration, Supervision, Funding acquisition. **L. R.** Conceptualization, Methodology, Software, Data curation, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – Review & Editing, Project administration. **A.B.** Review & Editing, Supervision, Funding Acquisition. **J. B., J. N., P. O., A. R. L.** Conceptualization, Methodology, Software, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – Review & Editing. **C. F., C. Z.** Methodology, Software, Formal analysis. **L. F.** Investigation, Review. **M. M., S. R., R.A.** Conceptualization, Methodology, Investigation, Visualization, Writing – Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. A.B. has ownership interests in firms that render services to industry, some of which may capture and store CO_2. A.B. has served on review committees for research and development at ExxonMobil and TotalEnergies, oil and gas companies that are also active in CCTS. V.B. has been part-time employee of Neustark, a Swiss start-up between April 2023 and February 2024; M.M. is scientific advisor of Neustark, compensated with equity in the company.

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Data Availability

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Appendix A. Environmental Impacts of Pioneering CCTS Chains

While the goal of CCTS chains is the reduction of global warming intensity of the industrial point sources, they unavoidably lead to other environmental impacts. Thus, we analyse 15 additional environmental impact categories besides GWI to quantify the extent of burden-shifting. For this purpose, we use the Environmental Footprint methods, version 3.0, to quantify the environmental impacts [48]. The environmental impacts for all pioneering chains shown in Fig. A.13 include direct and indirect emissions (i.e., scope 1, 2 and 3).

In contrast to the functional units defined in Chapter 3.4, the environmental impacts are determined for 1 ton of CO_2 captured, conditioned and transported to the nearest harbour. Thereby, to enable a comparison between the four pioneering chains, each environmental impact is normalized to the corresponding impact of the chain from Niederurnen.

The Niederurnen chain has the highest environmental impact in 6 out of 16 categories, while it only achieves the lowest impact in one category. The impact categories where the Niederurnen chain achieves the highest impact are dominated by the transportation step, accounting for more than 50% of the total impact in the respective categories. The high share in impacts of the transportation step result from the distance between Niederurnen and the harbour in Rotterdam, which is more than twice as large as the distance for the other pioneering chains.

The HC Górażdże chain has the largest environmental impact in 5 out of 16 impact categories. These impact categories are dominated by the utilities for the capture and conditioning step, contributing to more than 50% of the environmental impact. The Polish electricity grid mix depends heavily on the combustion of fossil fuels, such as coal, leading to a high environmental impact in many categories. In the category "*Eutrophication: Freshwater*", this is particularly evident with an impact nine times greater than the impact of the Niederurnen chain. In 2 out of 16 impact categories, the Górażdże chain achieves the smallest environmental impact.

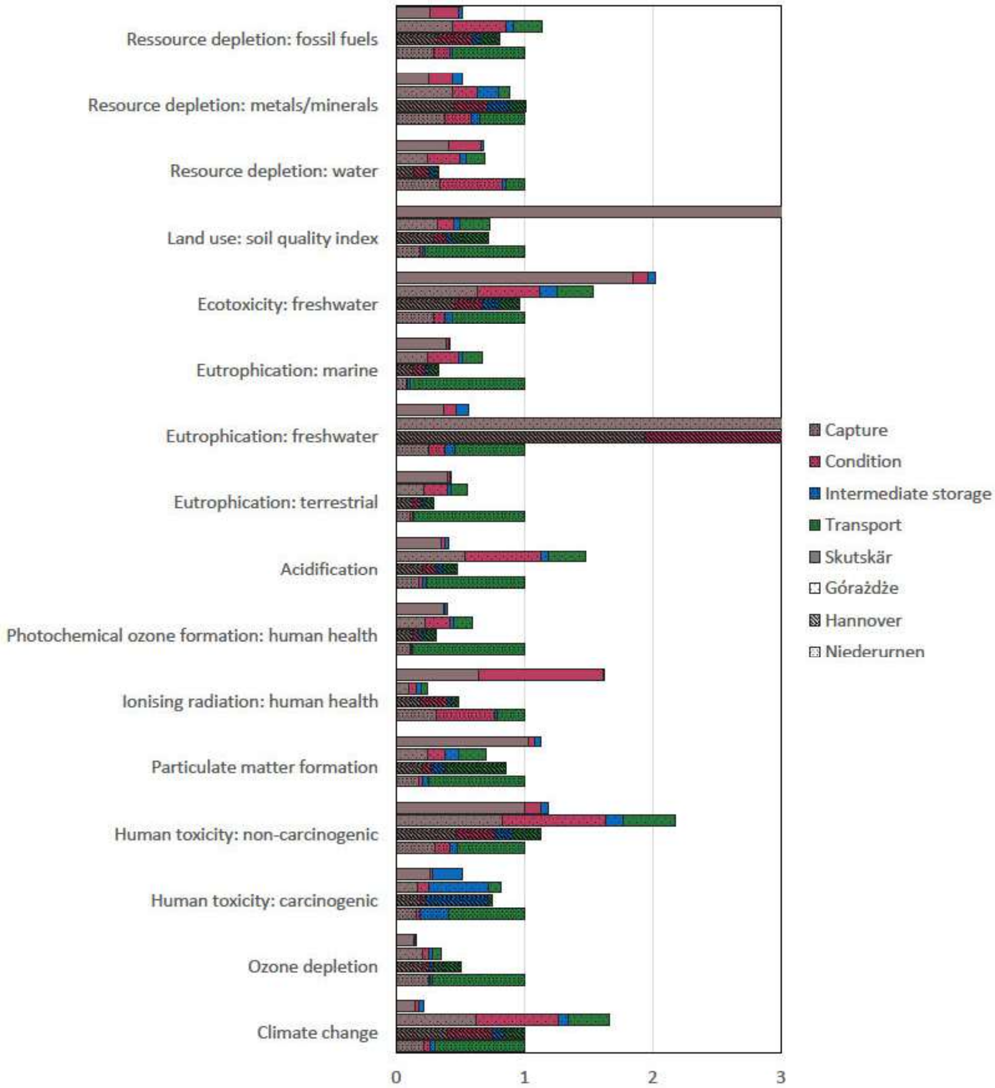

Figure A.13: LCA results for all pioneering chains including direct and indirect emissions (i.e., scope 1, 2 and 3) normalized by the impacts of the chain from Niederurnen. Thus, the Niederurnen chain has a value of 1 in each impact category. Note that "*Eutrophication: Freshwater*" and "*Land use: Soil quality index*" extend over the axis limits.

The chain from Skutskär shows the best performance in 7 of the 16 analysed impact categories. The Skutskär chain benefits from the Swedish electricity mix, mainly based on renewable and nuclear power and the fact that no transport step is required due to direct harbour access. However, the Skutskär chain has the largest impact in 4 categories. These impacts are mainly driven by the use of biomass boilers to generate the steam for the capture process and, in the case of the "*Ionising radiation: Human health*" impact category, by the large share of nuclear power in the Swedish electricity grid mix. Thereby, the impact on "*Land use: Soil quality index*" exceeds the impact of the Nierderurnen chain by a factor of 4.

The chain from Hannover achieves the best performance in 6 of the 16 impact categories while having the largest impact in only one impact category. However, it should be noted that the "*Eutrophication: Freshwater*" impact is 5 times larger than for the Niederurnen chain. Similar to the Górażdże chain, the impact can be attributed to the local electricity grid mix.

Appendix B. Network of feasible connections

Fig. B.14 shows the network of feasible connections from KVA Linth to the harbor of Rotterdam considered in this work, i.e., based on existing transport technologies and following established connections (with the exception of truck transport which is possible at any location with road access). This network can be converted into a simple directed graph, which can subsequently be used to apply the Yen's algorithm to compute the K most economical pathways [42].

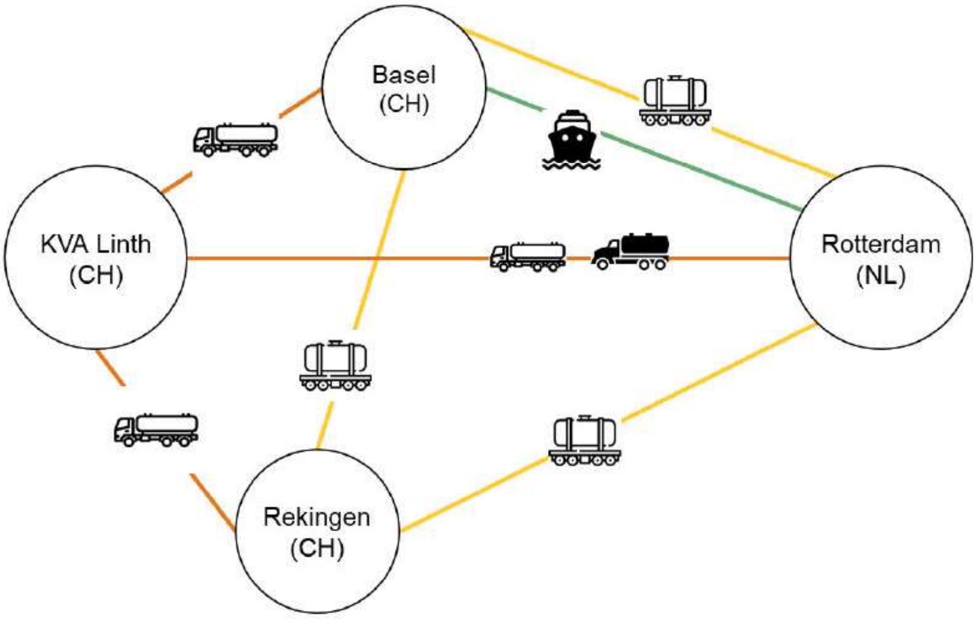

Figure B.14: Network of feasible connections from KVA Linth to the harbor of Rotterdam.

Appendix C. Techno-economic analysis framework

Appendix C.1. Economic boundaries

This section specifies the main assumptions considered to perform the economic evaluations. All economic assessments are reported on a 2020 basis. In cases in which all costs are not directly available in 2020 prices, investment costs must be adjusted to the correct level of prices [61]. This will be preferably done using the DACE index for process installations in Germany, generated by the Dutch Association of Cost Engineers (DACE), which generates indices to indicate the change of actual prices in the Netherlands and outside the Netherlands. When necessary, exchange rate are also be used to convert costs into Euro. Yearly average values for the DACE are given in Table C.5, and exchange rates from key relevant currencies to Euro are given in Table C.6.

Table C.5: Yearly DACE indexes.

Year	DACE index
2015	100
2016	102
2017	105
2018	107
2019	103
2020	TBA

Table C.6: Average exchange rates for 2020.

Currency	1 €
Norwegian kroner (NOK)	10.7228
Swedish krona (SEK)	10.4848
Polish złoty (PLN)	4.4430
Swiss francs (CHF)	1.0705
US dollar (USD)	1.1422

Appendix C.2. First-of-a-kind and Nth-of-a-kind

"FOAK" (First-of-a-kind) type of cost estimates reflect projects which have higher costs in the early stages of commercialization. With accumulated capacity and the associated accumulated experience, the costs of a project are reduced. Once the technology is mature, projects become "NOAK" (Nth-of-a-kind). The guidelines for FOAK and NOAK estimations are based on

Roussanaly et al. [32], where a detailed justification of some of the choices can be found.

FOAK projects can lead to higher investment costs than NOAK due to a variety of reasons. Some typical reasons for the higher investment cost are:

- Sub-optimal and oversized design
- Additional construction costs due to retrofitting
- Higher margin from contractors to face the risk of cost overrun
- Delays in construction
- Additional safety measures
- Additional spare and redundant equipment
- Higher process contingencies
- Higher system contingencies
- Stricter material selection and design standards
- Higher escalation cost during planning and construction
- Higher discount rate to reflect risk premium
- Lower levelized capacity factor

While these additional costs can have a more significant impact on CO_2 capture and conditioning, also CO_2 transport may be impacted. Indeed, while CO_2 transport via pipeline is a quite mature technology, other system like train, trucks, barges, and ships can be less mature, resulting in higher investment costs due to similar factors such as sub-optimal design, additional construction costs due to retrofitting, higher margin from contractors to face the risk of cost overrun, delays in construction and additional safety measures.

Operating costs are impacted to a smaller extent but are also higher for FOAK projects than for NOAK projects. Reasons for higher fixed operational costs for FOAK projects are:

- Higher regulatory fees due to a higher regulatory cost exposure
- Higher professional services due to additional legal support in the form of supplier warranty management, claims management and overall commercial risk mitigation
- More tools and equipment required for maintenance
- Higher lease expenses because FOAK facilities are expected to operate for a shorter period of time and thus pay higher lease rates
- More training required, especially for unique FOAK technology, for technicians, plant operators and plant engineers
- Higher property taxes and insurance due to a lack of prior commercial experience.

In this work, the pioneering chains are evaluated with a FOAK, or near FOAK, approach, especially on the capture section. The rationale behind this choice is to reflect the expected cost of the implementation of such chains as early movers. However, the Skutskär chain is also evaluated with a NOAK approach in order to appreciate the impact of such assumption. Table C.7

lists the factors that are changed, as well as their values, when applying a FOAK or NOAK approach.

Appendix C.3. Capital investment

A Bottom-Up approach (BUA) is used to estimate the total capital requirement of the CO_2 capture and conditioning process, while a Top-Down Approach (TDA) is adopted for the transport part of the pioneering chains.

Appendix C.3.1. Bottom-up approach

This approach is organized along the following steps:

- First, the direct cost of all relevant equipment of the considered process must be evaluated. It is worth noting that the direct cost is the sum of the Equipment Cost and the Installation Cost.
- The Total Direct Cost without process contingencies (TDC') is then calculated by summing up the direct cost of all units.
- The Total Direct Cost (TDC) with contingency is then calculated by adding the appropriate process contingency factor in order to reflect the technology maturity of the process considered. To be consistent with the maturity assumption implied by the FOAK cost basis, higher process contingencies than for a NOAK cost basis are considered. In particular, 20% for process contingencies is included for the pioneering chains. In addition, a system contingency factor of 10% is also included to reflect additional capital costs related to the integration of the CO_2 capture and conditioning process with the industrial plant. This cost is unique to initial installations of a new technology.

Table C.7: Factors for FOAK and NOAK approach.

	FOAK	NOAK	Unit
General data			
Discount rate	10	8	%
Years of operation	20	25	y
From TDC to TPC			
Process contingency	20	10	%TDC'
System contingency	10	0	%TDC'
Indirect costs	25	15	%TDC
Project contingency	40	30	%EPC
From TPC to TCR			
Owner's costs	10	7	%TPC
Start-up - Modifications	3	2	%TPC
Start-up - Spare parts	0.5	0.5	%TPC
Start-up - Labour cost	6	3	mro*
Start-up - Maintenance, materials, chemicals and consumables	1	1	mro*
Start-up - Fuel	2.5	0.25	mro*
Interest over construction			
Allocation over years of contruction			
Year -3	20	0	%
Year -2	30	40	%
Year -1	30	30	%
Year 0	20	30	%
Overnight factor	1.159	1.091	

*Months of regular operation

- The Engineering, Procurement and Construction costs (EPC) are then calculated by adding the indirect costs.

- The Total Plant Cost (TPC) is then calculated as the sum of EPC cost and project contingency estimated following the AACE 16R-90 guidelines. Considering the level of modelling detail, a project contingency cost of 40% is deemed appropriate.

- The Total Capital Requirement (TCR) is finally calculated as the sum of TPC, the owner costs, spare parts, modifications, interest during construction and the start-up cost. The owner cost, spare parts, modifications are set as percentages of the TPC (10, 0.5 and 3% respectively). The interest during construction is calculated, at the end of each subsequent year, assuming that the construction costs are shared over a 3.5-year construction period following a 20/30/30/20 allocation. Finally, the start-up costs are evaluated considering 6 months of maintenance, operating and support labour, 2 months of materials, chemicals, and consumables costs and 2.5 months of fuel costs

A geographic location factor, shown in Table C.11 is also considered.

Appendix C.3.2. Top-down approach

A top-Down approach can be used to estimate the EPC of the plant, which is based on the following steps:

- The EPC is estimated directly, based on equipment supplier estimates of EPC costs for the entire plant. The cost estimates through this approach by equipment suppliers are typically based on current technology maturity and uncertainties.

Table C.8: Process contingency factor at different levels of technology maturity.

Technology Status	Process Contingency Cost (% TDC without contingencies)
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules have been operated	5-20
Process is used commercially	0-10

Table C.9: System contingency cost at different levels of technology maturity.

Technology Status	System Contingency Cost (% of total process capital for all newly integrated components)
First commercial scale project (FOAK)	0-20
Second or third commercial projects	0-10
Fourth and fifth commercial projects	0-5
All subsequent commercial projects	0

Table C.10: Project contingency based on the AACE 16R-90 guidelines.

Estimate Class	Design effort	Project contingency cost (%-EPC)
Class I (similar to AACE Class 5/4)	Simplified	30-50
Class II (similar to AACE Class 3)	Preliminary	15-30
Class III (similar to AACE Class 3/2)	Detailed	10-20
Class IV (similar to AACE Class 1)	Finalised	5-10

Table C.11: Geographic specific factors.

Location	Materials cost factor	Labour productivity factor	Labour cost factor
The Netherlands	1.00	1.00	1.00
Eastern Europe	0.92	1.28	0.40

- The TPC is then calculated as the sum of the EPC cost and project contingency estimated following the AACE 16R-90 guidelines reported in Table C.10. Considering the level of modelling detail, a project contingency cost of 40% is deemed appropriate.

- The TCR is finally calculated following the same approach outlined for the BUA.

Appendix C.4. Operating costs

The annual average capacity factor (CF) of a plant reflects the fraction of product actually generated in a year relative to the maximum possible generation, i.e., for the same plant operated for a year at the full rated capacity. The higher the CF, the lower the cost per unit of product. While the CCTS chain is expected to operate to normal load after a few years, it is assumed that the first two years of operation will have operation levels reduced to account for ramping up of operation, because of technical issues, etc. Thus, during the first two years of operation, capacity factors of 40% and 65% are assumed, respectively, while industry-specific capacity factors (presented in Table C.12) are considered afterwards.

Appendix C.4.1. Maintenance, insurance and labour costs

The fixed operating costs include maintenance, insurance, and labour costs, and are estimated as follows:

- Insurance and local property taxes: The total annual cost of insurance, local property taxes and miscellaneous regulatory and overhead fees is to be a total of 2% of TPC.

Table C.12: Industry-specific capacity factors.

Industry	Industry-specific capacity factor	Reference
Cement	91.3%	[32]
Waste to Energy	80.0%	Internal project communication
Pulp and paper	95.9%	[32]

- Maintenance costs: Maintenance costs include costs of preventive maintenance, corrective maintenance (repair and replacement of failed components) and periodic replacement of materials. The maintenance costs correspond to 2% of the TPC excluding periodic replacement of materials which are defined based on the process. It is worth noting that the 2% considered for the maintenance costs also includes maintenance labour (which correspond to 40% of this 2%).

- Labour costs: Labour costs include operating labour, administrative and support labour. The operating labour costs are estimated based on the number of employees and a 'fully burdened' cost of labour, including social security payments that are in turn estimated based on the geographical location and considering a 5-shift pattern. When the information is not available, 60 k€/year per employee is to be assumed. This corresponds to the average of the Euro area (27 countries). Administrative and support labour costs are also included and are assumed to be equal to 30% of the operating and maintenance labour cost. Compared to a mature commercial technology, a FOAK facility can be expected to have significantly more equipment suppliers, contractors, consultants, and other personnel over an extended period of time. To account for this, the man-hour costs are increased 2 times compared to that of a commercial facility during the first three years of operation.

The labor cost levels are based on the Labour Cost Survey performed by Eurostat, the statistical office of the European Union. The data relate to total average hourly labor costs and to the labor cost categories "wages and salaries" and "employers' social security contributions plus taxes paid minus subsidies received by the employer" [62].

Table C.13: Labor cost levels for industry except construction (compensation of employees plus taxes minus subsidies).

Country	Annual labour costs in thousand Euro (k€/year)
Euro area (27 countries)	60
Sweden	86
Poland	22
Germany	87
Switzerland	60

Appendix C.4.2. Utilities and consumables costs

The variable operating costs include material utilities consumption such as electricity, natural gas, process water, and chemicals. The costs of the main utilities and consumables are evaluated based on the process energy and mass balance and the costs presented in Table 2. Certain utilities such as electricity and steam can be obtained at different costs depending on the source, amount, and location.

The cost of electricity for industrial sites is based on the average National European electricity energy prices, see Table 3.

The cost of steam for industrial sites are specific to the heat supply strategy considered, see Table 2f.

Finally, additional operating costs can also be expected in the first years of operation, especially for a demonstration project due to learning and training time, inefficiency, and so on. Utility consumption is therefore assumed to be 15% higher than the basis during the first three years of operation [35].

Appendix C.5. Project valuation

In order to the CO_2 avoidance cost, two project finance related characteristics are of importance: the discount rate and the project duration. Here, a real discount rate (i.e., without inflation) of 10% is considered in order to perform the project financial valuation. This is higher than commonly considered in NOAK type of estimates as FOAK projects lack prior operating experience, which results in a risk premium compared to the discount rate of a NOAK project. Similarly, a project economic lifetime of 20 years will be considered. This duration is shorter than the commonly used 25 years for NOAK estimates as FOAK project face significant long-term uncertainties (economic, political, etc.) related to the implementation of FOAK projects.