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Citation for the original published paper (version of record):
Roshan Kumar, T., Beiron, J., Marthala, V. et al (2025). Enhancing early-stage techno-economic comparative assessment with site-specific factors for
decarbonization pathways in carbon-intensive process industry. Carbon Capture Science and Technology, 14. http://dx.doi.org/10.1016/j.ccst.2024.100338

Carbon Capture Science & Technology 14 (2025) 100338

Contents lists available at ScienceDirect

Carbon Capture Science & Technology

journal homepage: www.elsevier.com/locate/ccst

Full Length Article

Enhancing early-stage techno-economic comparative assessment with site-specific factors for decarbonization pathways in carbon-intensive process industry

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ARTICLE INFO

Keywords:
Techno-economic analysis
Process industry
Carbon capture and storage (CCS)
Retrofit
Steam cracker plant
Site-specific costs

ABSTRACT

Site-specific factors are expected to influence the indication of cost-optimal decarbonization technology for the carbon-intensive process industry. This work presents a framework methodology to enhance the comparative analysis of decarbonization alternatives using site-specific techno-economic analysis, incorporating pertinent site-specific factors to obtain an enhanced indication of the optimal decarbonization solution. Site-specific cost factors such as energy supply options, space availability, site-layout constraints, local CO_2 interconnections, forced downtime, and premature decommissioning are considered. Qualitative site-specific factors and technology-specific attributes are assessed via expert elicitation with a retrofitability assessment matrix, generalizable to other process industries considering their site-level conditions. The framework methodology is demonstrated with a steam cracker plant case study, considering post-combustion CO_2 capture and pre-combustion CO_2 capture with hydrogen-firing in the cracker furnaces as decarbonization options. Results complemented with factor-specific sensitivity analysis highlight the extent of cost-escalation due to site-specific factors. The primary cost-contributing factor to retrofitability was the impact on production in existing sites, followed by the opportunity cost of utilizing valuable space on-site. Finally, pre-combustion CO_2 capture was found to be the optimal solution, offering significant site-specific advantages, with the lowest CO_2 avoidance cost and reduced overall risk over the residual lifetime of the host plant.

1. Introduction

Carbon capture and storage (CCS) is essential to decarbonize carbon-intensive industries such as cement, steel, oil refining, and petrochemicals. Rapid large-scale deployment of CCS in these industries is required in the next decade (2025–2035) to meet the net-zero CO_2 emissions targets of the European Union (EU) by 2050 (European Commission, 2018). Such a deployment requires rapid and reliable techno-economic performance assessment of competing technological options for CO_2 avoidance to identify viable business cases for plant operations with net-zero CO_2 emissions. Early-stage techno-economic analyses[1] (TEA) are commonly applied to evaluate the technical and economic performance of different CCS technologies integrated with carbon-intensive process plants. TEA combines process modeling and engineering design with economic analysis to assess the overall economic viability of various chemical process design options. Such comparative TEA studies often use standardized economic assumptions and parameters to ensure fair comparability. However, due to differences in costing methodology and its inherent assumptions, such comparative studies often lead to wide variability in results (van der Spek et al., 2017b), impeding a clear identification of a cost-optimal design or technology choice.

Efforts have been made to systematize the early-stage TEA methodology for CCS. Rubin et al. (2013) first proposed a common costing methodology for CCS in fossil-fuel power plants, addressing challenges such as the non-comparability of CCS cost information and heterogeneity in CCS nomenclature. Numerous studies have since applied standardized TEA methods (Roussanaly et al., 2021) to compare different decarbonization pathways for various process industries (Biermann et al., 2019; Garðarsdóttir et al., 2019). Standardizing CCS costing methods involves harmonizing cost escalation factors and economic assumptions to ensure reliable and comparable results (Roussanaly et al., 2021; Rubin, 2012), where the term "standardized" implies an established CCS

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[1] The various stages cost estimation for a typical CCS project can be found in Greig et al. (2014). This work uses the term 'early-stage' for cost estimation encompassing scoping to feasibility study estimations, while the term 'advanced stages' implies cost estimations for the financial investment decision (FID) prior to the startup and execution of the CCS project.

https://doi.org/10.1016/j.ccst.2024.100338
Received 29 August 2024; Received in revised form 10 November 2024; Accepted 11 November 2024

Nomenclature

Abbreviations

AACE	Association for the Advancement of Cost Engineering
ANF	Annualization factor
AR	Annual revenue
AVO	Avoidable
CAP	Cost of CO_2 capture
CAC	Cost of CO_2 avoided
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CEPCI	Chemical Engineering plant cost index
COR	Cost of retrofitability
DP	Decarbonization pathways
DT	Decarbonization technologies
EPC	Engineering, procurement, and construction costs
ELT	Economic lifetime
FEED	Front-end engineering design
FG	Flue gas
HPU	Hydrogen production units
IC	Indirect cost
MEA	Monoethanolamine
NG	Natural gas
NGCC	Natural gas combined cycle power plant
NOAK	N^{th} of a kind
O&IC	Owner's cost and interest during construction
OLT	Operation lifetime
OPEX	Operational expenditure
PC	Process contingency
Post-CCS	Post-combustion carbon capture and storage
PP	Process plant
Pre-CCS	Pre-combustion carbon capture and storage
PSA	Pressure swing adsorption
RLT	Residual lifetime
RWGS	Reverse water-gas shift
SF	Spatial footprint
s-TEA	Standardized techno-economic analysis
SV	Space-value
TCR	Total capital requirement
TDC	Total direct cost
TDCPC	Total direct costs with process contingency
TEA	Techno-economic analysis
TPC	Total plant costs
VF	Value function

Symbols

A100	Reactor section
A200	Primary fractionation and ethylene recovery section
A201	Product upgrading section
A300	Utilities section
A400	Tank farm section
A500	Wastewater and effluent treatment section
A600	Available space (Greenfield)
C	specific cost (in €/tCO_2)
C_p	Annual average price of product *p*
DS	Deployment scenario
i	Interest
j	Year (decarbonized plant operation)
L	Length
P_p	Production output of product *p*
VF_l	Linear space-value function
VF_{nl}	Non-linear space-value function
Y_0	Year of construction of a process plant
Y_1	First year of operation of a process plant
Y_{cy}	Current year of operation
Y_{dy}	Planned year of commissioning of CCS equipment
Y'_{dy}	CCS deployment year synchronized with turnaround year
Y_{ex_ey}	Extended plant decommissioning year
Y_{ey}	Scheduled plant decommissioning year (end-of-life)
Y_{mo}	Year of scheduled major overhaul/ turnaround year

Subscripts

a	annum or operational year
A	land value constant
avo	avoided
c	component
cap	captured
cons	consolidated
cont	contribution to the cost of retrofitability (captured/avoided CO_2)
el,dp	electricity consumption in a specific decarbonization pathway
eq	equivalent
f	scaling factor
FD	forced downtime
fg	fluegas
frag	fragmented
k	plant capacity
liq	liquefied CO_2
n	total number of products
netw	network
OC	opportunity cost
OC_total	CO_2 capture/avoidance costs comprising estimated OC and the baseline capture/avoidance costs
p	product
PD	premature decommissioning
PD_total	CO_2 capture/avoidance costs comprising estimated PD and the baseline capture/avoidance costs
q,dp	steam (heat) consumption/generation in a specific decarbonization pathway
r	growth rate
ref	reference
SC	Steam cracker
seg	segment
SF	spatial footprint
x	plant area (variable)

costing methodology with common nomenclature and consistent cost escalation guidelines.

Significant efforts have been made to address the wide variability and uncertainty in results from standardized TEA by using uncertainty analysis methods (van der Spek et al., 2017b; 2019). The expected accuracy range from these standardized early-stage TEA methods ranges from 15 % to +50 % (Christensen and Burton, 2005). While these methods are often sufficient for early-stage pre-screening and feasibility studies, it is, however, not uncommon to see significant cost escalation at advanced stages of project development, as highlighted by Grieg et al. (2014). These cost escalations stem from increasing levels of scope and project details, with cost estimates based on front-end engineering design (FEED), which incorporates site-related conditions of a specific process plant. Several recent large-scale amine-based post-combustion CCS projects have been terminated due to significant project cost escalation at advanced design stages, unfavorable market conditions, or improvement in alternative decarbonization solutions that were initially deemed infeasible (Global CCS Institute, 2023; National Energy Technology Laboratory, 2018). These deployment failures highlight the limitations of early-stage standardized TEA methods in accurately identifying *cost-optimal* decarbonization alternatives. The term 'cost-optimal' hereinafter refers to a decarbonization option incurring the lowest CO_2 avoidance cost (compared to a non-exhaustive list of alternative decarbonization options) at a host process plant.

One of the primary limitations of standardized TEA methods is that site-related constraints and opportunities are often neglected to provide a fair comparison between different technological options for a specific process industry. This limitation could lead to a severe disparity between the early-stage indication of cost-optimal CCS technology and its actual economic performance after deployment at a specific plant. Key CCS economic indicators, such as CO_2 capture (CAP) and avoidance costs (CAC), and the capital and operational expenses of the CCS technology, calculated using standardized TEA methods, are typically calculated based on a specific reference plant and its process characteristics (e.g., flue gas properties such as CO_2 concentrations and capacity). These cost indicators are often generalized and presented as industry-specific costs (Kuramochi et al., 2012). Subsequently, these industry-specific costs in the literature are extracted to energy-systems level studies providing critical information to decision-makers, for example, country-specific marginal abatement cost curves (Johnsson et al., 2020), cascading costs to end-users and consumers (Hörbe Emanuelsson and Johnsson, 2023; Subraveti et al., 2023). Although these studies aim to provide indicative cost estimates for CO_2 avoidance for various carbon-intensive process industries at an aggregated level, such generalization of CCS cost estimates inherently assumes that all plants within that industry sector have similar conditions. However, in reality, both process characteristics and site-related conditions can differ significantly from plant to plant within the same industry sector, thereby affecting the final cost of CO_2 avoidance.

More recently, Roussanaly et al. (2021) introduced guidelines for estimating costs for CCS in the process industry that inherently have varying site-specific features. For example, energy supply options and site-specific retrofitting costs were identified as key factors expected to vary considerably from one plant to another. Martorell et al. (2022, 2023) compared differences in detailed cost estimates from FEED studies for CO_2 capture via amine scrubbing for two natural gas combined-cycle power plants with nominal capture capacities of 197 and 129 tCO_2/h. This comparative study highlighted that site-related factors, such as site layout (which determines the extent of flue gas conveying equipment), resource availability (e.g., water), and design choices for steam generation and cooling, contributed significantly to the final capital cost of the project. Therefore, neglecting site-related conditions in less rigorous TEA methods implies that the lowest-cost decarbonization solution for a process industry sector may not be universally applicable to all plants within that sector.

Attempts have been made to address site-specific cost factors in the past. For example, energy supply and retrofitting costs were identified as key site-specific cost factors expected to vary considerably from one process plant to another (Roussanaly et al., 2021). Hills et al. (2016) compared different CO_2 capture technologies with varying technology-readiness levels and discussed their technology-specific attributes that may hinder their direct integration (retrofitting) into the existing cement industry. Some technology-specific attributes presented in their work included operational complexity, process changes required in the host cement plant, impact on product quality, and retrofitability aspects, i.e., interconnections and spatial footprint of the capture plant. Space availability and CO_2 transportation infrastructure were deemed crucial requirements for all CO_2 capture technologies considered in their work. In their recent guidelines for CCS cost evaluation, Roussanaly et al. (2021) presented different CO_2 interconnection configurations that may result from site layout constraints, such as space availability and multiple distant emissions point sources within plant boundaries. Furthermore, the sensitivity of the direct cost of flue gas ductwork to capacity and transport distance was addressed. However, the site-layout dependencies of the overall CO_2 interconnections and their corresponding costs were not presented by Roussanaly et al. (2021).

Apart from the aforementioned site-specific cost factors, factors such as the potential lock-in effect of newly installed decarbonization equipment have not been explored before. Lock-in effects refer to the potential sunk costs resulting from stranded assets. Stranded assets may result from a lifetime mismatch between the host plant and the newly installed decarbonization equipment, requiring premature decommissioning or the inability to adapt to future process changes (e.g., feedstock switch or increased process electrification) in the process plant and impede its economic competitiveness in a future decarbonized market. In addition, different decarbonization technologies with differing spatial footprints could also result in an opportunity cost, which could lead to sub-optimal use of valuable space within existing plant sites that can no longer be used for expanding production or deploying emerging low-carbon production technologies. These cost factors are essential for the comparison and selection of technologies, requiring a generalized approach that can be applied at an early stage of process-level TEA to help prepare a host-site for subsequent installations towards net-zero or negative CO_2 emissions.

In conclusion, although there have been a number of recent efforts to improve standardized TEA methods, there is still a clear need for further work to close the gap between early-stage TEA assessment and actual expected project costs in order to decrease the upfront uncertainty that enables informed decisions toward deployment of cost-optimal decarbonization solutions. Ultimately, the existing limitations of early-stage standardized TEA methods in identifying the cost-optimal decarbonization solution for carbon-intensive process plants risk delaying the implementation of CO_2 reduction measures. Thus, this work aims to develop generalized methods to quantify site-specific factors relevant to large-scale industrial sites and provide cost estimation tools to quantify their impact that may influence the final choice of decarbonization solution for a specific process plant.

A framework methodology is presented that introduces *site-specific TEA* to obtain enhanced indications of the lowest-cost decarbonization solution when comparing different decarbonization alternatives. The framework methodology is demonstrated through a case study on a steam cracker plant that emits approx. 650 kt/yr of fossil CO_2. This case study plant was chosen because its transformation is expected to require multiple process technologies to facilitate decoupling from fossil feedstocks, as well as technologies for capturing CO_2 emissions for permanent storage or utilization. Secondly, these plants are often situated in large chemical clusters, with complex material and energy flows with downstream chemical industries. The optimal selection of technologies in these settings is particularly challenging due to spatial constraints and the limited time available—specifically the finite number of turnarounds before the target year for achieving net-zero emissions.

The case study presents a detailed comparison of two commercially available decarbonization pathways – post-combustion CO_2 capture (Post-CCS) and pre-combustion CO_2 capture (Pre-CCS). The Post-CCS option adopts an amine-based capture process with a benchmark monoethanolamine (MEA) solvent to capture CO_2 from the flue gases. In contrast, the Pre-CCS option involves valorizing methane-rich fuel gas, produced on-site as a co-product, to produce hydrogen, which is then utilized as the primary fuel in the cracker furnaces. Compression and liquefaction processes are assumed to be the same for both pathways investigated. The novelty and main contribution of the work lies in advancing early-stage TEA methods for integrated CCS systems with a methodical approach to quantifying and incorporating site-specific factors of host process plants, which have not been quantified or published in previous early-stage ex-ante TEA. The method introduced in this work enables the enhancement of published industry-specific CCS cost information to a specific-plant of interest, considering its site-level factors. Finally, the method, demonstrated through the case study of a steam cracker plant, illustrates its applicability to other large-scale process plants, such as refineries.

The paper is organized as follows: Section 2 introduces the theoretical background for the site-specific factors introduced in this work;

Table 1
Definitions of terminologies used in this work.

Terminologies	Definition
Decarbonization pathways (DP)	Pathways or options arising from *different technological alternatives* (e.g., pre-combustion, post-combustion, or oxyfuel combustion) and measures (e.g., fuel switching, direct or indirect process electrification) that can be implemented to achieve net-zero CO_2 emissions at an unabated process plant.
Decarbonization technologies (DT)	*Set of process equipment* required to enable a specific decarbonization pathway. For example, post-combustion CO_2 capture would require a CO_2 capture technology (chemical/physical/cryogenic) in combination with compressors and CO_2 purification or CO_2 liquefaction units, depending on the mode of CO_2 transportation. Together, these sets of process (decarbonization) equipment enable the post-combustion CCS decarbonization pathway.
Standardized TEA (s-TEA)	Techno-economic analysis method based on (rigorous[a]) technical models and established/standardized[c] bottom-up cost models (rigorous/intermediate[b]), as commonly applied to estimate the cost of a project deploying one or more emerging/mature process technologies (Franco et al., 2021; Gerdes et al., 2011).
Site-specific TEA	Techno-economic analysis method based on rigorous[a] technical models and detailed[b] bottom-up cost estimation incorporating defined site-specific quantitative and qualitative factors, applicable to large-scale process plants, expected to impact the cost of CO_2 avoidance at a specific site.

[a] Thorough physical models based on first principles incorporating detailed flowsheets, mass and heat transfer, detailed kinetics, and recycles, as defined by Roussanaly et al. (2021).

[b] Rigorous implies detailed economic estimates based on an exhaustive equipment list using individual escalation/scaling factors, including all capital and operations costs; Intermediate implies combinations of bottom-up and top-down methods using partial equipment lists and Lang/Hand type escalation factors, as defined by Roussanaly et al. (2021).

[c] The term standardized implies engineering-economic cost estimate methodology, with standardized cost escalation factors with guidelines for economic assumptions, e.g., methods used in NETL assessment studies (Gerdes et al., 2011).

Section 3 provides an overview of the framework methodology and describes the methods used; Section 4 describes the set-up of the steam cracker case study; Section 5 analyzes the differences in cost estimates and the influence of each site-related factor on the investigated decarbonization pathways, followed by a discussion on the method, limitations, and implications of the investigated site-specific factors in Section 6. Finally, the main conclusions are presented in Section 7.

2. Site-specific factors with significant impact on costs for decarbonization

This section introduces the site-specific factors of process plants identified in this work that include spatial and time constraints expected during the selection and installation of decarbonization technologies. These site-specific factors include the opportunity costs associated with spatial footprints of decarbonization technologies, site-layout-dependent CO_2 interconnections, and the cost associated with forced downtime and premature decommissioning, which are described in more detail in the following subsections. Table 1 summarizes the definitions of terminologies used in this work.

2.1. Implication of spatial footprint of decarbonization technologies

In the context of decarbonization, existing process plants require CCS-retrofitting[2] that often competes with other investment decisions (e.g., expansion projects aimed at increasing production or installation of emerging low-carbon technologies). Hills et al. (2016) highlighted the availability of land as the most critical issue for the roll-out of CCS at existing cement plants, where the existing plant layout and its restrictions were identified as key factors that could influence shutdown periods during installation. In general, achieving net-zero CO_2 emissions targets at existing process plants necessitates installing process equipment, which, in turn, requires space within the host plant. If the host plant lacks space, achieving zero-CO_2 emissions would require rearrangement or removal (decommissioning) of existing process units (redundant or operational) to accommodate the decarbonization equipment. In contrast, if there is sufficient space, the layout of the site and the nature of the available space, i.e., either brownfield or greenfield (with and without environmental permits and access to process utilities), is expected to further escalate the final cost of decarbonization. Therefore, space availability at a specific site would ultimately determine whether or not a specific decarbonization option can be realized in practice, irrespective of whether it is the lowest-cost decarbonization solution based on s-TEA methods.

In addition, considering that some process plants may have sufficient space for installing CCS equipment, it raises the question of whether the available space is optimally used if occupied by decarbonization equipment. An upfront CCS retrofit (early mover investment) is likely to incur an opportunity cost compared to installing an emerging low-carbon production technology in the available space within the plant. For instance, full or partial replacement of existing steam crackers with emerging technologies such as e-crackers (Borealis Group, 2021) or thermochemical recycling of mixed plastic waste (Cañete Vela et al., 2022; Thunman et al., 2019) which generate revenue with relatively low CO_2 emissions, could offer greater economic benefit than a CCS retrofit as a stopgap measure. Therefore, this work considered the following questions– (i) How can the physical (spatial) footprint of decarbonization technologies be quantified at an early stage based on limited plant data such as flue gas properties? (ii) What is the opportunity cost of occupying valuable available space at a specific plant site?

2.1.1. Spatial footprint estimation

Accurate estimation of spatial footprint requirements is therefore crucial to either reject or select decarbonization technologies at an early stage, considering site-level constraints. Incumbent methods for spatial footprint estimation of decarbonization technologies include linear and modular approaches. The linear approach entails linear scaling of an absorption-based CO_2 capture plant with the net capacity of a power plant (pre-retrofit). This approach was deemed unreasonable by Florin and Fennell (2006), who reviewed data published before 2010 and instead recommended a modular approach to scale footprint with capture components. Berghout et al. (2015) used a combination of linear[3] (for columns) and modular approaches[4] (for auxiliary units) to estimate the total physical footprint of the CO_2 capture plant. Berghout et al. (2015) stated that while the modular approach needed to be validated with technology providers, the linear approach (relationship between equipment capacity and surface area) would nevertheless underestimate the total spatial footprint compared to the modular ap-

[2] Defined as undertaking process changes to existing plants (Kemp, 2007).

[3] A linear relationship between column diameters and CO_2 flow rates (at different concentrations) was derived to compute the spatial footprint of the absorbers and stripper.

[4] Component-wise scaling of individual equipment in the capture plant using spatial footprint estimates extracted from FEED studies (see Eqn. 6).

proach. Notably, their results highlighted that even when assuming the linear scaling approach, most industrial sites in the studied industrial cluster would have insufficient space to accommodate a CO_2 capture plant.

Firstly, these findings confirm that space availability in existing sites and, thereby, the inherent spatial footprint requirement of competing decarbonization technologies are crucial technical indicators that must be quantified at an early stage. Secondly, these findings highlight a need for meticulous data curation of spatial footprint estimates from FEED studies on CCS retrofits to various industrial processes to understand the industry-specific and technology-specific determinants influencing their space requirement at a host site. FEED studies with detailed engineering of each component and their placement on a specific site, accounting for site-layout constraints, are ideal for such early-stage estimation of spatial footprint. Therefore, an alternative approach to the incumbent spatial footprint estimation methods for amine-based CO_2 capture technology is introduced in this work. More specifically, publicly available FEED studies with detailed engineering designs of the capture plant are categorized based on the type of industry to derive an industry-specific correlation between flue gas properties (flow rates and CO_2 concentrations) and their minimum area requirements. The spatial footprint (SF) estimation method is described and compared with incumbent methods in Section 3.5.1.1.

2.1.2. Opportunity costs

The spatial footprint requirements of a certain decarbonization pathway could be directly linked to the opportunity cost of selecting one decarbonization alternative over another at a specific site. For example, differing spatial footprints of the different decarbonization pathways could allow or hinder the future possibility of replacing end-of-life core production units with newer low-carbon production technology and, thereby, varied opportunity costs. Decarbonization alternatives could range from using widely deployed commercial technologies (e.g., end-of-pipe CO_2 capture) to process technologies (e.g., autothermal reformers) that have been adapted for decarbonization but lack large-scale demonstration (e.g., oxyfuel or hydrogen-firing). Additionally, there are emerging low-carbon process technologies that are still under development, with anticipated commercialization and deployment in the short term. Finally, the option of operating the process plant unabated until its end of life, with an additional cost of emitting CO_2, should be considered, provided this does not result in the withdrawal of the plant's operating permit. The opportunity costs associated with available space on-site are seldom quantified in s-TEA methods to assess the comparability of different decarbonization options and their site-specific cost of CO_2 avoidance. Therefore, this work presents a generalized method to quantify the opportunity costs associated with the investigated decarbonization options, using their estimated spatial footprints in relation to the available space at a host process plant. The calculation methods are described in Section 3.5.1.

2.2. Site-layout-dependent interconnection costs

The CO_2 interconnections required within the plant boundaries typically include flue gas ducting, capture solvent piping, and CO_2-rich gas/liquid pipelines, which may differ in lengths and capacities. In addition, space constraints within plant boundaries are expected to impose differing interconnection configurations. The corresponding costs for transporting CO_2 within the plant boundaries (to the fence) are expected to vary from plant to plant, within and between different process industries (Hills et al., 2016; Roussanaly et al., 2021). Fig. 1, adapted from Roussanaly et al. (2021), illustrates different CCS layout configurations with different interconnection lengths for a single-point source emissions plant to transport CO_2 from the point source to the plant fence. In Fig. 1, configuration (c) and configuration (d) represent the two extreme cases depicting the most and least cost-effective network configurations, respectively, due to the high cost associated with flue gas ducting (Roussanaly et al., 2021). The CCS cost evaluation guidelines (Roussanaly et al., 2021) stress that interconnection costs, which could be significant, are often overlooked until detailed engineering is done based on the constraints of a specific site layout. For example, interconnection cost (including in-plant CO_2 transportation and utility piping) added 16–35 €/tCO_2 to the baseline avoidance cost estimates for different CO_2 retrofit scenarios at a refinery (IEAGHG, 2017).

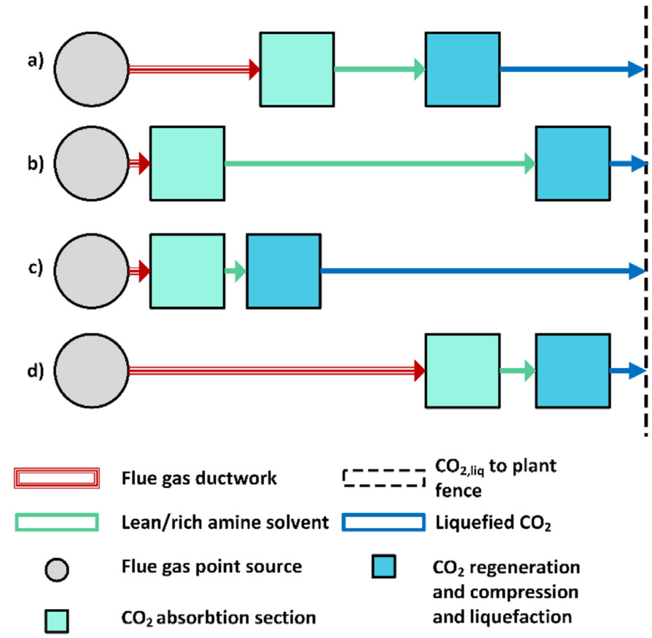

Fig. 1. Illustrative example of site-layout-dependent CO_2 interconnections for transporting CO_2 from single-point source emissions to the plant fence on space-constrained sites, adapted from Roussanaly et al. (2021), where additional interconnection configurations for multiple-point source emissions can be found.

In this work, we consider *site-layout dependent interconnection costs*, with a systematic approach for evaluating site layouts where a merit order for placement of capture components on available space is presented. This merit order is based on transport distances to the emissions point source and the likelihood of rearrangement or removal of existing assets. This approach is complemented with a cost-estimation tool for flue gas ductwork and piping for capturing solvent and liquified CO_2 that incorporates the physiochemical properties of the transported fluid. Detailed description of the method and input data are presented in Section 3.5.2.

2.3. Energy supply options

As highlighted in recent CCS costing studies, energy supply options available at the specific site were expected to significantly affect operational costs, total capital expenditure, and the eventual cost of CO_2 avoidance (Biermann et al., 2022a; Martorell et al., 2023). In addition, CO_2 avoidance is inherently tied to the indirect CO_2 emissions associated with energy supply options, i.e., steam and electricity that are typically specific to an individual site, based on its location and existing site-energy system. In addition, operational costs could also vary significantly due to temporal variations in residual heat available on-site (Biermann et al., 2022a). To this end, this work considers the existing and future site-energy systems as site-specific factors, for which their corresponding influence on the cost of CO_2 avoidance is evaluated (Section 5.2).

2.4. Forced downtime

Major revamps, including implementation of decarbonization technologies, are typically undertaken during scheduled maintenance and revision shutdowns. Synchronization of scheduled revamping projects and CCS plant construction and timing of system integration is pertinent to avoid significant cost overruns (Hills et al., 2016). The potential cost of forced downtime (or plant stoppages) is an important factor to consider when estimating the range of retrofitting expenses for different CCS technologies with a host process plant, considering the level of operational experience and the complexity of integrating the process technologies with the host plant. One such example is integrating oxyfuel combustion technology into a cement plant. According to Hill et al. (2016), such integration is expected to entail "increased design and maintenance complexity," which has a clear negative impact on the ease of retrofitability of this technology. Increased retrofitability challenges naturally imply a higher risk of forced downtime beyond scheduled annual shutdowns or major overhauls.[5] Depending on the industry, cost overruns due to delays in commissioning, which require the host plant to be non-operational, could be significant. For example, such costs have been estimated at 3 M$ a month for a 1 Mt/y cement plant, which represents 40 % of the total operational cost of an unabated plant (Hills et al., 2016; IEA ETSAP, 2010; Lafarage, 2007). Therefore, this work presents a generalized approach to estimating cost overruns due to forced downtime to enhance the technology-specific comparison and better represent industry-specific cost escalation.

2.5. Delay in CCS adoption/deployment (lock-in effect)

The cost of decarbonization could also escalate depending on the timing of the CCS deployment relative to the residual lifetime of a host process plant. For example, Rohlfs and Madlener (2013) studied decarbonization pathways for coal power plants and compared the CCS retrofit strategy with alternate options, such as a newly built coal plant with capture components. Their work concluded that premature decommissioning of an existing coal power plant and alternatively constructing a new power plant, including CCS, outperformed a retrofit strategy applied to an existing unabated power plant and a capture-ready power plant. Their findings highlight site-specific and technology-specific aspects of installing new CCS equipment on existing industrial assets.

First, CCS investments in process plants with shorter residual lifetimes are not warranted as the newly installed CCS equipment is required to run their whole design lifetime or even longer, with high utilization hours, to minimize the overall cost of decarbonization. However, the residual lifetime of most process plants is plant-specific as they depend entirely on their commissioning year and their future restoration/re-investment, which could extend their lifetime beyond the design lifetime. In addition, their scheduled major overhauls[6] also differ in timing and duration within and between different process industries. For example, major overhauls in refineries and other petrochemical industries typically occur on a four-to-six-year cycle, lasting around three to four weeks (Lawrence, 2012).

Secondly, each decarbonization technology differs in its dependence on the host plant characteristics. For example, an end-of-pipe amine-based CO_2 capture technology inadvertently depends on host plant characteristics such as flue gas flow rate and CO_2 concentration. Future process changes, such as feedstock or other technical changes, could imply that the capture plant must operate outside its intended design parameters. For example, a steam cracker plant processing heavier hydrocarbon feedstock would have relatively higher CO_2 concentrations than an steam cracker plant processing lighter hydrocarbon feedstock, thereby impacting the performance of the capture plant post-retrofit to the host process plant. Therefore, this work considers the lock-in effect of different decarbonization technologies, which arises from their tendency to be dependent on the process characteristics of the host plant.

If a decarbonization pathway with all its associated equipment can operate as a stand-alone plant, it can be considered independent or not locked into the host process plant. Such is the case, for example, for hydrogen production units, which include steam methane reformers and CO_2 capture equipment. These units, designed to valorize methane-rich fuel gas in a steam cracker plant, could still operate as stand-alone low-carbon hydrogen production units provided they have access to the natural gas grid or methane-rich fuel gas from other co-located chemical plants. In contrast, an amine-based capture plant is relatively locked in and cannot be expected to operate after the decommissioning of the host process plant. Thus, the risk of stranded assets can only be avoided if the newly installed equipment has an alternate value beyond the lifetime of the host plant. An early-stage assessment of how these costs escalate could determine how different decarbonization alternatives compete against each other in the context of a specific process plant. To this end, this work presents a generalized site-specific method to estimate the technology-dependent impact of delay in CCS deployment on the cost of decarbonization for process plants.

Fig. 2 depicts an illustrative example of the lock-in effect of newly installed decarbonization/CCS equipment to the host (unabated) process plant. The figure illustrates a process plant with a design lifetime of 50 years, where each vertical gridline corresponds to a five-year operation period. The extension of plant lifetime with restoration/re-investment is indicated in blue. Major overhauls are indicated with red-dashed vertical lines, occurring every ten years since the year of commissioning (Y_1) of the process plant. In Fig. 2, the difference between the current year of operation (Y_{cy}) and its design lifetime is the residual lifetime of the process plant. Ideally, the design economic lifetime of the CCS equipment (CCS_{ELT}) must be greater or equal to the residual lifetime of the process plant (PP_{RLT}) to achieve the lowest cost of decarbonization. Assuming the process plant synchronizes the CCS plant construction ahead of the next scheduled major overhaul, in this exemplary illustration, the operational lifetime of the CCS plant (CCS_{OLT}) is less than its design economic lifetime (CCS_{ELT}), thereby influencing the economic viability of this technology. An exception is that the deployed CCS technology is independent of the host plant, or the investment in a CCS technology was made in conjecture with a planned re-investment in the host plant to extend its lifetime. The aspects mentioned above are typically excluded from comparative TEA studies. However, the above example underlines that the cost-optimal choice of CCS technology is site-specific and must be assessed when comparing different decarbonization technologies. The cost calculations for this site-specific factor are described in Section 3.5.4.

3. Methods

3.1. Overview of framework methodology

Fig. 3 presents an overview of the framework methodology that includes two parts: i) the conventional methodology used (indicated in grey) to compare decarbonization pathways for the carbon-intensive process industries, and (ii) the enhanced comparative analysis incorporating site-specific factors (highlighted in green) that are expected to influence the cost of decarbonization, hereinafter referred to as site-specific TEA.

In general, the incumbent methods consist of the following steps — (i) Extracting key performance data for core processes of a reference process plant, e.g., material and energy flows, flue gas compositions, and site-energy systems, i.e., steam and fuel gas systems; (ii) Pre-screening of decarbonization pathways: selecting promising alternatives and extracting technology data for further evaluation; (iii) Process synthesis and integration: Defining the system boundary to evaluate the refer-

[5] Longer duration than annual scheduled periods (typically a month). This is an industry-specific factor.

[6] Also referred to as extended maintenance shutdowns or turnarounds (Lawrence, 2012).

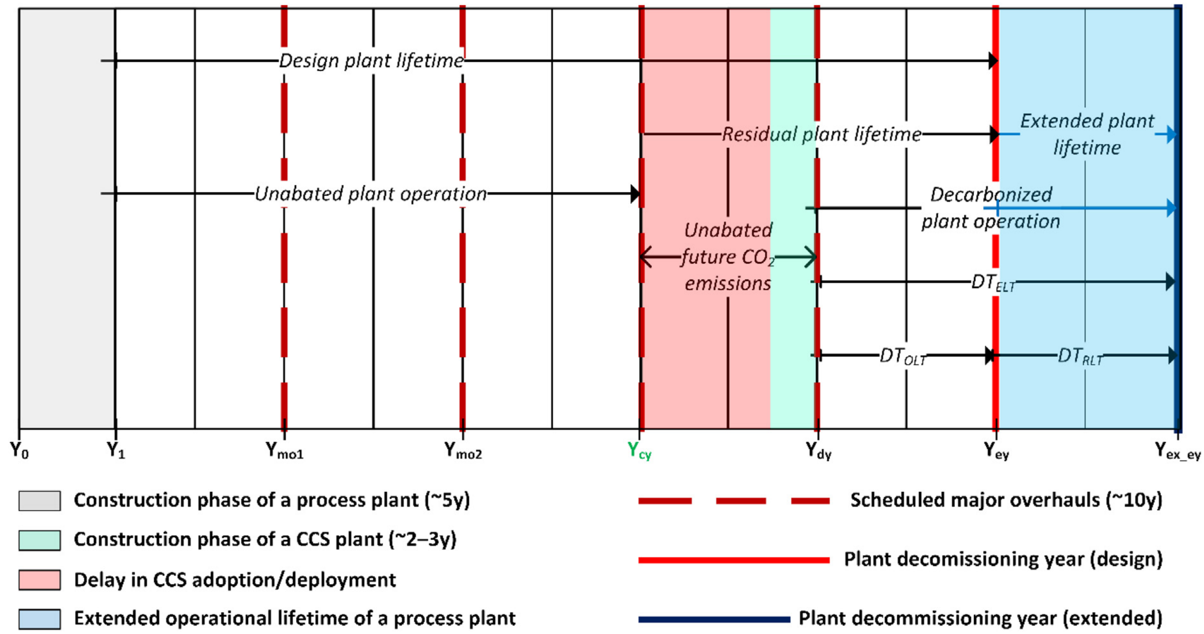

Fig. 2. Illustrative example of delayed adoption/deployment of CCS relative to the lifetime of the host process plant. Each vertical gridline corresponds to a five-year operation period. Figure abbreviations: Y_0 – Year of process plant construction, Y_1 – First year of plant operation, Y_{mo} –Scheduled major overhaul year, Y_{cy} – Current year of operation, Y_{dy} – Planned year of commissioning of decarbonization equipment, Y_{ey} – Scheduled process plant decommissioning year, Y_{ex_ey} – Extended plant decommissioning year with reinvestments, DT_{ELT} – Economic lifetime of the installed decarbonization technology, DT_{OLT} – Expected operational lifetime of the decarbonization technology, DT_{RLT} – Residual economic lifetime of the decarbonization technology.

ence process plant's technical performance with and without the newly integrated decarbonization technologies to ensure a fair comparison, followed by developing rigorous process models of the process plant, and the associated decarbonization technologies. Next, heat and material balances from the developed models are used for energy targeting to improve the overall energy efficiency of integrated (decarbonized) processes; (iv) Key technical performance indicators from the integrated process models are extracted to evaluate economic performance using standardized TEA methods, which are complemented by sensitivity analysis on key economic parameters. Finally, an early-stage and industry-specific indication of the cost-optimal decarbonization pathway with its associated technologies is obtained. Note that the term industry-specific implies that only process characteristics are considered, and no site-specific information is used in the s-TEA method. Thus, the resulting CO_2 capture and avoidance costs are specific to the reference process industry, not the plant. Alternatively, such cost data and indications on optimal decarbonization technology for a process industry could be taken directly from the literature to initiate the site-specific TEA, as described below.

Further enhancement of the comparison of decarbonization pathways can be achieved with the site-specific approach: (v) Identification and extraction of site-specific factors expected to influence the final cost of decarbonization for the case-study plant; (vi) Classification of site-specific factors as qualitative or quantitative; (vii) Estimating cost of quantitative factors (described further in Section 3.5), which together provide a cost of retrofitability (COR) for each decarbonization pathway. (viii) Calculation of the site-specific cost of CO_2 capture (€/$tCO_{2,ss\text{-}cap}$) and avoidance (€/$tCO_{2,ss\text{-}avo}$) based on the sum of CO_2 capture (€/$tCO_{2,cap}$) and avoidance cost (€/$tCO_{2,avo}$) estimates from the s-TEA method and the estimated COR (€/$tCO_{2,cap/avo}$); (ix) Qualitative factors (technology and site-level attributes) expected to influence the choice of a specific decarbonization pathway over another can be evaluated via expert elicitation using a retrofitability assessment matrix (described further in Section 3.6); (x) Finally, results from the qualitative retrofitability assessment, sensitivity analysis, and site-specific costs can be combined and visualized in a diagnostics diagram (described further in Section 3.6.2) to obtain an enhanced visual indication of the optimal decarbonization pathway for the reference process plant. The framework methodology is developed for conducting early-stage cost assessments, corresponding to an AACE Estimate Class 3–4. The developed framework methodology was applied to a reference steam cracker plant (described in Section 4). Therefore, the subsequent description of the methodology is in the context of a steam cracker plant.

3.2. Pre-screening of decarbonization pathways

A straightforward pathway screening approach (step ii, in Fig. 3) was considered in this work by comparing two technologically mature[7] decarbonization pathways using commercially available process technologies. These include (i) post-combustion (Post-CCS) with end-of-pipe CO_2 capture with a fixed capture rate of 90 % and ii) pre-combustion (Pre-CCS) pathway to achieve the same level of decarbonization as the Post-CCS (i.e., CO_2-emissions free steam crackers) at the reference steam cracker plant. This pathway screening approach was chosen to avoid uncertainties regarding the maturity of emerging process technologies and thereby simplify the demonstration of the framework methodology. Nevertheless, the comparison could be expanded to emerging decarbonization pathways with differing technology maturity, provided experience curve methods are incorporated. Guidelines on combining engineering-economic and experience curve methods can be found elsewhere (Roussanaly et al., 2021; Rubin, 2019).

3.3. Modeling of decarbonization processes

Post-CCS and Pre-CCS processes were modeled (steady state) in Aspen Plus V12.1 and simulated with the reference plant data (Table 5,

[7] Technologically mature implies all associated process technologies are commercially available. Note that the lack of large-scale successful demonstrations is common to both considered decarbonization pathways.

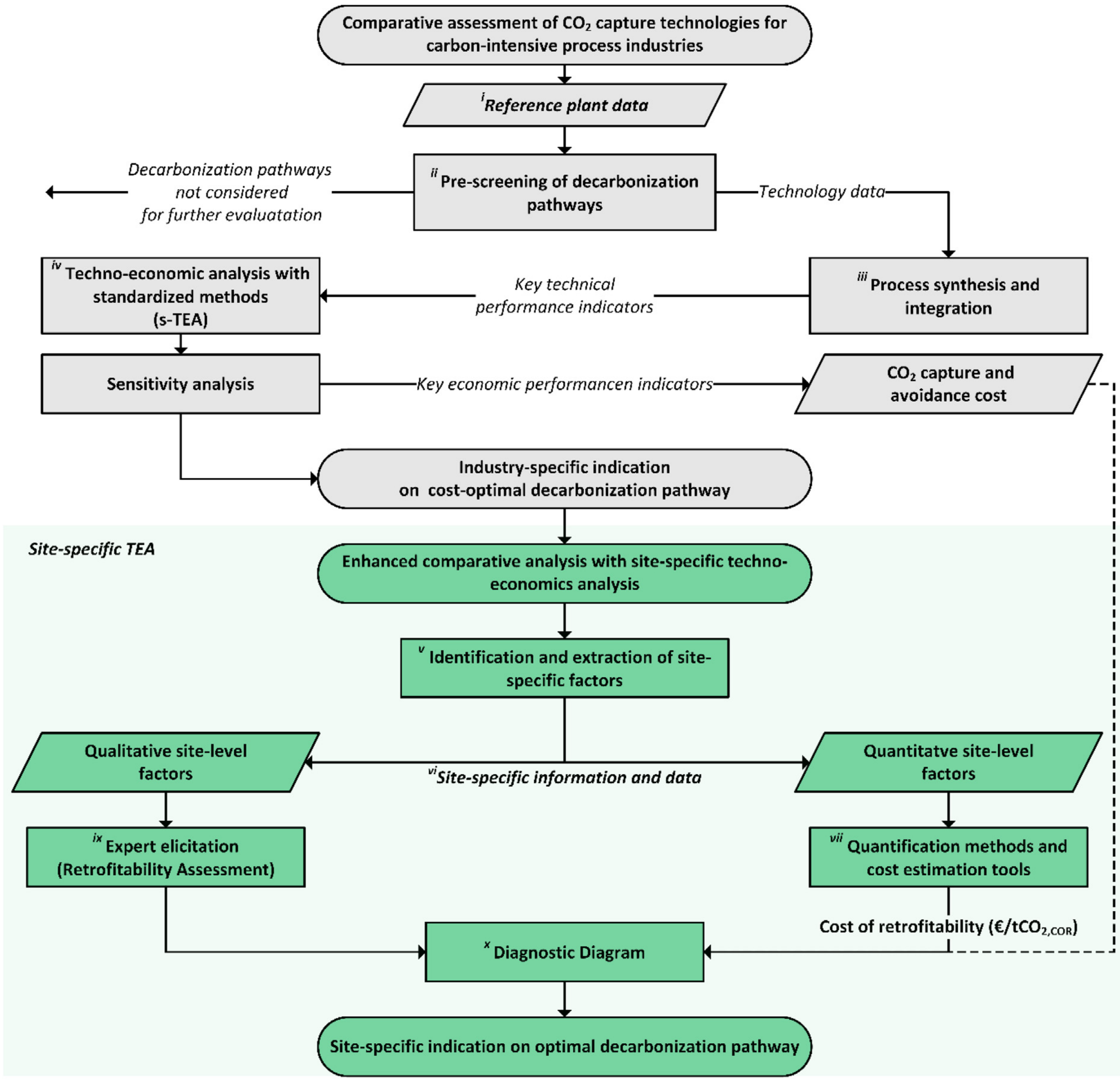

Fig. 3. Overview of the framework methodology applied in this work to enhance the comparative analysis of different decarbonization pathways, incorporating site-specific factors (indicated in green) into incumbent comparative assessment methods (indicated in grey). The oval symbol indicates the start/end of the two parts of the framework methodology, parallelograms indicate input/calculated data, and rectangles indicate methods. The dashed line indicates the technology-specific cost of CO_2 capture and avoidance using standardized techno-economic analysis methods.

Section 4). The Post-CCS process model uses an updated rigorous rate-based CO_2 absorption cycle model assuming a 30 wt.% aqueous benchmark-amine solvent (MEA, monoethanolamine), based on previous work by the authors (Kumar et al., 2023), which was originally developed by Garðarsdóttir et al. (2015) and Biermann et al. (2018, 2022a, 2022b). The Pre-CCS process assumes an equilibrium-based model, which includes an air-separation unit for O_2 production, an autothermal reformer for steam-methane reforming reactions, water-gas shift reactors for increasing hydrogen yield, and pressure-swing adsorption units for hydrogen separation and purification. A detailed modeling description and validation of the MEA model and the Pre-CCS model can be found elsewhere (Kumar et al., 2023; Thim, 2022). The CO_2 compression and liquefaction processes were modelled in the previous work by the authors (Kumar et al., 2023), based on models developed by Deng et al. (2019). System boundaries, detailed process flowsheet diagrams, key assumptions, and process parameters of the process models are provided in the Supplementary Material S.1.

3.4. Standardized techno-economic analysis (s-TEA)

A hybrid top-down/bottom-up capital cost estimation method, adapted from Biermann et al. (2022a) is applied in this work, with an illustration provided in Supplementary Materials S.1.3. The top-down approach entails extracting data reported in the literature or using vendor data for a whole unit (including all associated equipment), typically reported as engineering procurement and construction (EPC) costs. This approach was used for equipment for which ample cost data was available in the literature for entire subsystems, such as air separation units in the Pre-CCS model. The bottom-up approach was used for equipment for which EPC costs were unavailable. In this case, energy and material flow data from the developed process models were used to dimension each piece of equipment. The direct cost of each equipment was obtained from direct cost data or regressed direct cost functions derived from the Aspen Process Economic Analyzer. The regressed direct cost functions presented by Biermann et al. (2022a) were used to determine the size and cost for all major equipment in the Post-CCS model.

Table 2
Default economic parameters and assumptions.

CAPEX	Units	Value	Comments/References
Cost year and currency	–	2018, Euro	
Cost Index		CEPCI	
Location factor		0.995	Sweden relative to the Netherlands (Ali et al., 2019)
Plant life (n)	Years	20	CCS plant, based on the remaining lifetime of the reference steam cracker plant (2 years construction time and 18 years operational lifetime (Biermann et al., 2022a)
First of a kind or Nth of a kind		N^{th} of a kind	All CCS equipment considered in the study is technologically mature and commercialized. Thus, expected NOAK estimates (see Roussanaly et al., 2021 for description) are presented.
Discount rate (i)	%	10	Assumption
Cost escalation factors			
Total Direct Costs (TDC)	$€_{2018}$	$\Sigma\ (DC_1 + DC_2 + ..\ DC_n)$	DC refers to the direct cost (equipment + installation costs) of components, dimensioned using a process model and cost estimated from regressed cost functions from Aspen Process Economic Analyzer.
Process Contingency (PC)	% of TDC	15	Total Direct Cost with Process Contingency (TDCPC) is obtained with the assumed PC.
Indirect Costs (IC)	% of TDCPC	25	Engineering, Procurement, and Construction costs (EPC) are obtained with the assumed IC.
Project contingency	% of EPC	40	Total Plant Costs (TPC) are obtained with the assumed project contingency. (Roussanaly et al., 2021; Rubin et al., 2013b)
Owner's cost and interest during construction (O&IDC)	% of TPC	9.5	Total Capital Requirement (TCR) is obtained with the assumed O&IDC.
Annualization factor	ANF	8.51	Estimated for a discount rate of 10 % and plant life of 20 years; Calculated according to Berghout et al. (2015)
OPEX			
Maintenance + insurance costs (% of TPC)		4.5 %	(Biermann et al., 2022a)
Electricity price	€/MWh	60	Average of an electricity price ranging from 30 to 90 €/MWh (Roussanaly et al., 2021)
Natural gas price	€/MWh	21.6	Average of a natural gas price ranging from 3 to 9 €/GJ (Roussanaly et al., 2021)
Cooling water price	€/t	0.02	(Ali et al., 2019)
Steam price	€/MWh	28.4	Estimated assuming a boiler efficiency of 90 %, LP steam conditions (131 °C, 1.8 barg), and NG price of 21.6 €/MWh.
Solvent (MEA) costs	€/t	1700	(Biermann et al., 2019)
Reclaimer sludge disposal	€/t	300	(Biermann et al., 2019)
Caustic Soda	€/t	400	(Garðarsdóttir et al., 2019)
Labor costs	k€/a	411	Six operators and one engineer estimated labor costs for a carbon capture plant (Biermann et al., 2022a)
Operational hours	hours/a	8000	Assumption

Although no pre-commercial technologies were considered in the developed process models, a conservative approach is taken with assumed process contingencies of 15 % (% of the total direct cost), corresponding to an indicative technology readiness level of 7–8 (Gerdes et al., 2011). Based on recent guidelines for CCS cost evaluations (Roussanaly et al., 2021), a relatively higher project contingency (40 %) was assumed (in the s-TEA method), which corresponds to a concept/scoping study on an early-mover project (>10 and <20 successful demonstrations worldwide) (Greig et al., 2014; Roussanaly et al., 2021). Cost escalation factors, listed in Table 2, were applied to correspond to either direct costs or EPC costs for each piece of equipment based on the capital cost estimation approach (top-down/bottom-up) used. The list of equipment associated with Post-CCS (Fig. 6a) and Pre-CCS (Fig. 6b) are listed in Supplementary Materials S.3. Note that all cost data are adjusted and presented in 2018 Euros. As per Eqn. (1), the estimated total capital requirement (TCR) was annualized over the assumed design lifetime of 20 years for all associated DTs. The total annual costs are the sum of annualized CAPEX and the total annual operational costs ($OPEX_{total}$). The $OPEX_{total}$ costs include fixed (maintenance, insurance, and labor) and variable costs (fuel, electricity consumption, and other consumables).

$$CAPEX_{annualized} = \frac{TCR}{ANF}\left[\frac{M\Delta}{y}\right] \quad (1)$$

$$OPEX_{total} = OPEX_{fixed} + OPEX_{variable}\left[\frac{M\Delta}{y}\right] \quad (2)$$

$$\text{Equivalent } CO_2 \text{ avoided } \left(AC_{eq}\right) = \frac{e_{sc,ref} + e_{el,dp} \pm e_{q,dp}}{e_{sc,ref}} \quad (3)$$

$$CAP = \frac{CAPEX_{annualized} + OPEX_{total}}{m_{CO2,cap}}\left[\frac{€/y}{tCO_{2,captured}/y}\right] \quad (4)$$

$$CAC = \frac{CAPEX_{annualized} + OPEX_{total}}{m_{CO2,avo}}\left[\frac{€/y}{tCO_{2,avoided}/y}\right] \quad (5)$$

Key technical performance indicators included the equivalent CO_2 avoidance (AC_{eq}), calculated as per Eqn. (3), defined as the amount of CO_2 avoided ($m_{CO2,avo}$) relative to the host process plant without CO_2 capture with the same output production. It accounts for the indirect CO_2 emissions generated from the additional steam ($e_{q,dp}$) and electricity consumption ($e_{el,dp}$) of the CO_2 capture plant. In Eq. (3), the negative sign in $e_{e,dp}$ implies direct CO_2 emissions avoided from the existing steam generation utilities as a result of the excess heat recovered for steam generation from the newly installed decarbonization equipment. The cost of CO_2 captured (CAP) was defined as the ratio of the total annual costs of the CO_2 capture plant and the total absolute amount of CO_2 captured within plant boundaries, calculated as shown in Eq. (4). The annualization method (Roussanaly et al., 2021) was used to estimate the cost of CO_2 avoidance (CAC), shown in Eq. (5), where it is expressed as a ratio of total annual costs of the CO_2 capture plant to the total avoided CO_2 emissions.

3.5. *Site-specific techno-economic analysis*

3.5.1. *Opportunity cost of decarbonization pathways*

The estimation of the opportunity cost of occupying available plant space with decarbonization technologies was conducted in two parts — the spatial footprints of the selected decarbonization pathways were quantified (described in Section 3.5.1.1) first based on flue gas properties of the process plant, which was followed by using the quantified technology-specific spatial footprints to estimate the site-specific opportunity cost of occupying space available on-site, that could provide other alternative value to the process plant (described in Section 3.5.1.2).

3.5.1.1. Estimation of the spatial footprint (SF) of decarbonization pathways.

Post-combustion CCS plant: The SF estimation tool estimates the space required for installing an amine-based CO_2 capture plant, including compression and liquefaction units, at a specific site based on flue gas properties, i.e., flue gas flow rate and CO_2 concentration. The tool uses existing data for area requirements of Post-CCS plants to derive correlations for spatial footprint as a function of flue gas properties (see Supplementary Materials S.2). First, a list of area requirements was compiled from publicly available FEED reports for Post-CCS retrofit projects. Based on the level of detail of the reported values, they were classified as detailed, semi-detailed, or rough estimates. Detailed SF estimates were used as input data to the SF tool, which included engineering drawings, the layout of the CCS plant, and its placement within the host process plant. The semi-detailed and rough SF estimates either excluded detailed engineering drawings, the CCS plant layout and its placement considering the host site layout, or both. Therefore, these estimates were not used as input to the SF tool to limit uncertainties.

Consequently, the selected detailed SF estimates were further categorized based on the host industry type. This was done to obtain industry-specific influences on area requirements for Post-CCS plants. For instance, most reported SF estimates were primarily for Post-CCS retrofits on existing coal (~13 vol% CO_2 concentration in flue gases) and NGCC (~4 vol.%) power plants. Based on this data, SF estimation functions were regressed for each industry type to obtain their corresponding influence on spatial footprint based on their flue gas properties. These industry-specific regressed functions were plotted together on a 2D graph diagram, with the Y-axis indicating the spatial footprint (m^2) and the X-axis indicating the flue gas flow rates (kg/s). This enabled a max/min approach in the SF estimation tool concerning the CO_2 concentrations and flow rates. In the SF estimation tool, the validity range is set by the selected detailed SF estimates, primarily for NGCC and coal plants, which sets a CO_2 concentration range between 4 and 13 vol% CO_2 and the corresponding overlap region between the industry-specific flue gas flow rates. Using the tool, the SF of a Post-CCS plant for a specific site can be estimated based on the flue gas properties within these validity ranges via linear interpolation within the CO_2 concentration limits.

Pre-combustion CCS plant: The incumbent modular approach (Berghout et al., 2015; Blok and Nieuwlaar, 2016) for SF estimation was adopted for the Pre-CCS process, for which FEED studies were unavailable or lacked sufficient details. The modular approach involves quantification of the spatial footprint of individual components using literature data (Berghout et al., 2015) with component-specific scaling factors to determine the total spatial footprint of a decarbonization pathway, as shown in Eq. (6). Here, $A_{c,ref}$ denotes the space requirement of component 'c' in a reference plant, where S_c is the capacity of a component for a plant scale 'k' and $S_{c,ref}$ is the reference capacity of the component c at the reference plant. A scaling factor f_C of 0.67 and an additional margin ('M') of 20 % of the total computed area (A_k) for installation and maintenance was assumed.

$$A_k = \left(\sum_c A_{c,ref} \times \left(\frac{S_c}{S_{c,ref}} \right)^{f_c} \right) \cdot M \tag{6}$$

3.5.1.2. Opportunity cost of spatial footprint. The opportunity cost of the spatial footprint of decarbonization technologies was estimated based on the opportunity cost of occupying available land with decarbonization technologies, where the alternative use would be to maintain current production with an added cost of emitting CO_2 or installing emerging low-carbon olefins production technology at a later time.

Space-value graph: Fig. 4 illustrates the overview of the method to estimate the opportunity cost of decarbonization technologies at a specific site. First, the existing site layout of the plant is categorized based on the process design hierarchy[8] (Smith, 2016). The process design hierarchy is considered here to enable a generalized categorization of the site layout of different process industries with typically large spatial footprints (e.g., refineries), as illustrated in Fig. 4a.

In this work, a modified[9] onion diagram, shown in Fig. 4a, is introduced for generalized categorization of unit operations based on their importance to the overall production of a specific process plant. Based on this definition, the reactors (core-production process) were considered to be the most valuable equipment that enables production at a specific site, followed by equipment in the outer layers of the onion diagram. Fig. 4a includes an additional outer layer to represent space available at existing sites as brownfield and greenfield areas, i.e., areas currently occupied by redundant or non-operational units and empty plot space, respectively. The greenfield areas were placed as the outermost layer, assuming little to no contribution to plant production, and, due to higher costs expected for placing decarbonization equipment in greenfield areas as opposed to brownfield areas. The different layers in the modified onion-diagram are hereinafter referred to as plant sections.

In Fig. 4b, the X-axis of the plot corresponds to the total plant area (in m^2) represented with equal plant section areas (gray-shaded layers in Fig. 4a) for simplicity. The Y-axis corresponds to the total annual revenue of the reference plant, which was calculated based on a pro-rata basis, as shown in Eq. (7), assuming an annual average price (c) for each product (p) produced at the reference plant. The resulting 2D graph diagram (Fig. 4b) is hereinafter referred to as the space-value (SV) graph, which represents the value of each plant section based on their contribution to the total annual revenue. As the modified onion-diagram (see Fig. 4a) ranked the plant sections in increasing order of their value addition or contributions to the total annual revenue, accumulative site-specific value (SV) functions were assumed that represent the opportunity cost of occupying available space at different plant sections.

A conservative (max/min) approach was adopted by assuming a linear (VF_l) and non-linear (VF_{nl}) site-specific value function, exemplified with red and blue lines, respectively, in Fig. 4b. The two SV functions were assumed to represent the expected value addition range of each plant section to the total annual revenue. As shown in Fig. 4b, the maximum was set by a linear SV function, calculated as per Eq. (8), which implies that all plant sections are valued equally by the plant owner. In contrast, the minimum was set by a non-linear SV function, dependent on the existing assets at a specific plant site, which is described with an exponential growth function, as shown in Eq. (9), where 'A' denotes the exponentially increasing land value from the outer layers of the modified onion-diagram towards the inner plant sections, and 'r' denotes the growth rate. The independent variable 'x' denotes the plant area. The gradient of the exponential function is dependent on the type of process plant, as the physical footprint of its core-production units (reaction section), and their relative contribution to the total annual revenue is expected to vary from one plant to another.

$$\text{Total annual revenue} = \sum_{p=1}^{n} (P_p \cdot c_p) [€] \tag{7}$$

$$VF_l = \frac{\text{Total annual revenue}}{\text{Total plot area}} \left[\frac{€}{m^2} \right] \tag{8}$$

$$VF_{nl} = Ae^{rx} \left[\frac{€}{m^2} \right] \tag{9}$$

Merit order of space utilization: A merit order for space utilization (see Table 3) was applied to classify the available space within an existing

[8] Also referred to as the onion model for process design which illustrates the sequential nature of process design, where the synthesis and optimization of design parameters in the reactors section are prioritized first, followed by the subsequent layers of the onion diagram to obtain a complete design (Smith, 2016).

[9] Adapted to illustrate the increasing order of accumulative value addition or contribution to the total annual revenue of the process plant.

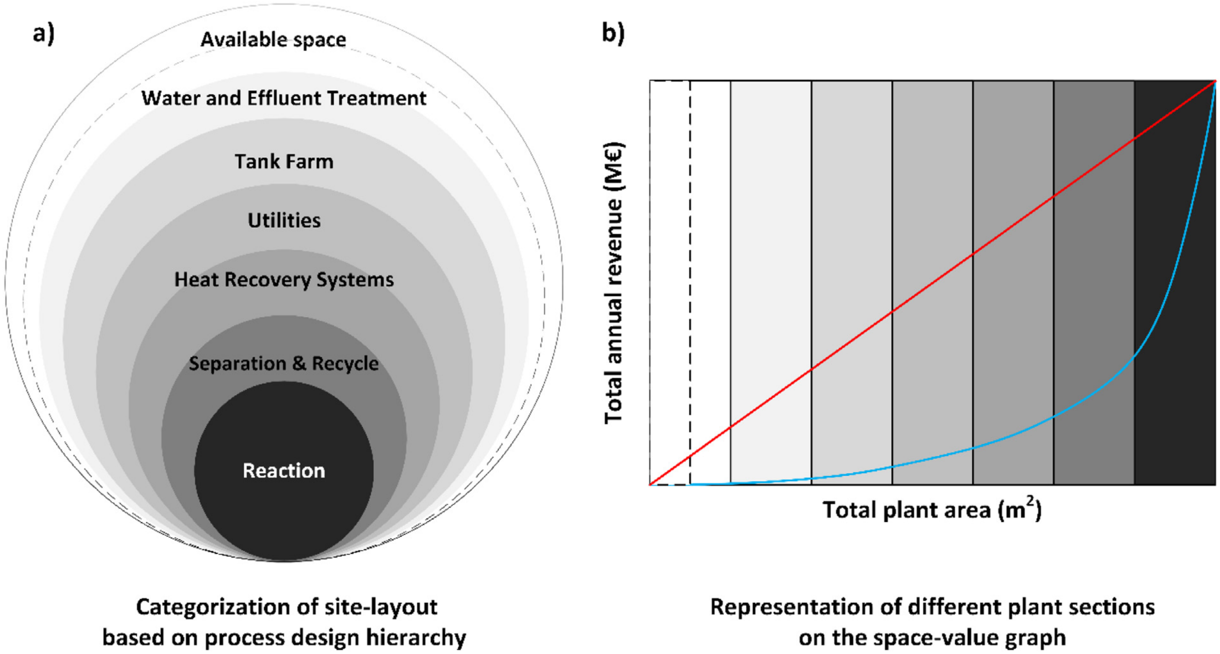

Fig. 4. (a) Categorization of the site layout of a process plant based on the process design hierarchy (Smith, 2016) and (b) its representation on the space-value graph, which represents the different plant sections from the onion diagram. Note that all gray-shaded layers in the diagram shown in subplot (a) are assumed to have equal areas and are arranged in subplot (b) in increasing order (from left to right) based on their cumulative value addition or contribution to the total annual revenue of the process plant. The dashed line indicates the categorization of available or allocated space for future expansion as brownfield and greenfield areas. Red and blue lines indicate the linear and non-linear space value functions.

Table 3
Classification of available space and corresponding merit order for space utilization within the existing process plants.

Type of available space	Class of available space		Examples
Brownfield	I	Unoccupied	Vacant space close to the emissions source due to decommissioning of existing units or allocated space for a later retrofit of CCS due to mandates on carbon-capture readiness (European Commission, 2008; Markusson and Haszeldine, 2010)
	II	Occupied with redundant and inactive units requiring rearrangement or decommissioning	Part of the core-production units approaching end-of-life, close to the emissions source
Greenfield	III	Greenfield areas	Unoccupied space allocated for expansion, typically away from the emission source

process plant to determine where decarbonization equipment could be placed on-site at an early assessment stage. The merit order was primarily based on the type of available space, i.e., brownfield or greenfield areas. It was assumed that unoccupied brownfield areas would be utilized first, followed by brownfield areas with redundant units (after removal/rearrangement) and greenfield areas, as listed in Table 3. Greenfield areas were placed last on the merit order of space utilization as they generally incur higher costs due to securing environmental permits, typically longer distances from emissions sources, and the lack of access to existing utility systems. Within brownfield areas, unoccupied regions were prioritized over occupied regions with redundant and inactive units. The proximity to the emissions sources was considered last, after the classification of space available on-site, as the CO_2 interconnection costs were expected to be significantly lower than the opportunity cost of occupying the available space.

Placement of decarbonization equipment: The placement and configuration of decarbonization equipment within a process plant were contingent on-site layout characteristics, such as the nature of available space and its specific location within the facility. Based on site layout constraints, the estimated total spatial footprint from the SF estimation tool (see Section 3.5.1.1) is plotted as a single vertical line (in yellow) for a consolidated configuration (see Fig. 5a) or with two or more vertical lines (see Fig. 5b) for fragmented configurations where the CCS equipment occupies different plant sections. Each vertical line represents the area occupied by CCS equipment/subsystems in the respective plant sections, which is subtracted from the right edge (representing the total area) of respective plant sections. Finally, the difference between the contribution of a specific plant section to the total annual revenue before and after the installation of decarbonization equipment was represented as lost annual revenue (AR_{loss}) corresponding to the plant-specific non-linear (VF_{nl}) and linear (VF_l) site-specific value functions on the SV graph. With this, the SV-graph estimates the opportunity cost in terms of lost revenue (potential) or notional loss incurred annually.

$$AR_{loss,VF_{nl}} \le DT_{sf,cons} \le AR_{loss,VF_l} \tag{10}$$

$$AR_{loss,VF_{nl,seg1}} + AR_{loss,VF_{nl,seg2}} \le DT_{sf,frag} \le AR_{loss,VF_{l,seg1}} + AR_{loss,VF_{l,seg2}} \tag{11}$$

$$C_{OC} = \frac{\sum_{j=0}^{RLT}\left(\left(DT_{sf_{cons/frag}} * RLT\right)/(1+i)^j\right)}{\sum_{j=0}^{RLT}\left(\left(\dot{m}_{CO_2\_cap/avo} * CO_{2_{avg\_tax}} * RLT\right)/(1+i)^j\right)}\left[\frac{€}{tCO_{2,cap/avo}}\right] \tag{12}$$

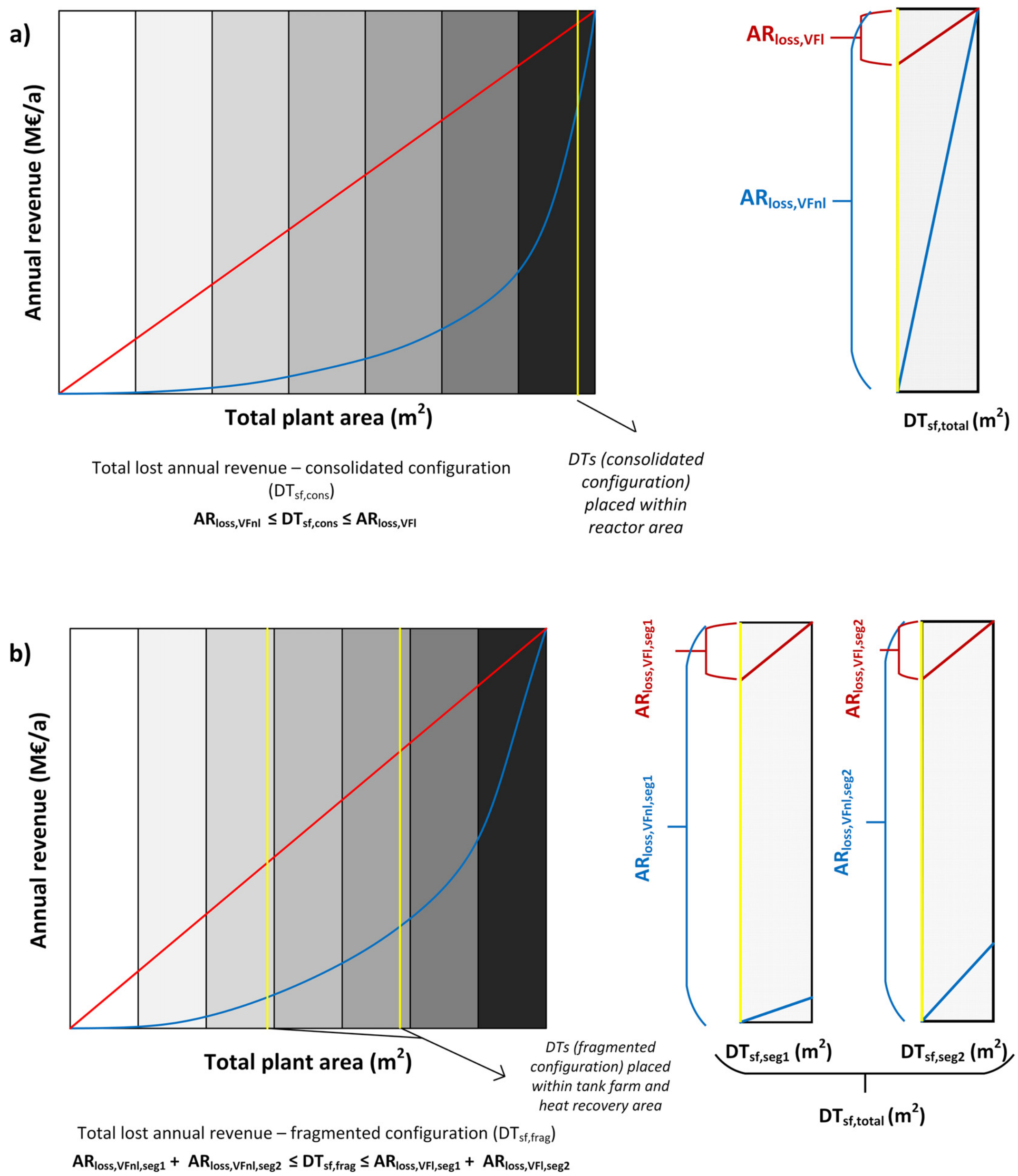

Fig. 5. Overview of the procedure for estimation of the cost of the spatial footprint of decarbonization technologies (DT) that is dependent on its layout configurations – a) consolidated configuration (all DTs in one area category) and b) fragmented configuration (distribution of DTs in several area categories). Abbreviations: SF – spatial footprint, AR – annual revenue, VF – value function, seg – segment.

$$C_{OC\_total} = CAC + C_{OC\_avo} \left[\frac{€/a}{tCO_{2,avo}/a} \right] \tag{13}$$

Opportunity cost calculation: The lost annual revenue (M€/a) range obtained from the SV graph, calculated as shown in Eqs. (10) and (11), for different placement configurations, was considered as forgone revenue over the lifetime of the host plant, as the space occupied by the decarbonization technologies prevents the installation of other alternatives for decarbonization with a delay in deployment or the possibility of operating the unabated process plant while incurring a direct operational cost in the form of EU-ETS permits price per tonne of CO_2 emitted. In contrast, the deployment of decarbonization technology avoids both CO_2 emissions and associated emissions costs. The net present value method (see Eqs. (12)) was used to discount the cumulative forgone annual revenue and averaged EU-ETS price avoided for the residual lifetime of the host process plant, as these cash flows are not realized until the end of a specific year of decarbonized operation.

The opportunity cost calculations were complemented with a sensitivity analysis for varying averaged prices for carbon permits or emissions rights under EU-ETS, ranging between 0 and 225 €/tCO_2 over the residual lifetime of a process plant to overcome the uncertainty of future CO_2 prices. The lower bound (0 €/tCO_2) was chosen to represent a scenario of unabated plant operation that is not subject to the effective EU-ETS permit price. Note that this lower bound also covers future scenarios of price fluctuations below the current EU-ETS price.[10] The upper bound represented the doubling of the EU-ETS permit price from the current price levels[5] in the long term. The cumulative forgone revenue

[10] EU-ETS average emission allowance price in the year 2022 ~81.3€/tCO_2. The EU-ETS permit prices reached an all-time high of 105.7€/tCO_2 in February 2023 (Statista, 2023b).

(opportunity cost) accounts for the net present value of the cumulative cost of EU-ETS permits avoided. The net loss/gain was divided by the cumulative absolute amount of CO_2 captured and avoided over its residual lifetime to obtain the technology-specific opportunity cost of CO_2 capture ($C_{OC,cap}$) and avoidance ($C_{OC,avo}$), respectively. The site-specific cost of CO_2 avoidance (C_{OC_total}), including the estimated opportunity costs, is calculated as shown in Eq. (13).

3.5.2. Cost of interconnections within plant boundaries

The site-layout-dependent interconnection costs, which include flue gas ductwork, solvent, and CO_2 piping, were assumed to be additional costs incurred as CAPEX during construction. A *network design hierarchy*, adapted from Berghout et al. (2015), was followed to determine the design and technical specifications of each component of the local CO_2 transportation network. The present work developed a simplified local CO_2 network cost estimation tool for the total CO_2 interconnection costs based on the network design calculation method (Berghout et al., 2015). The main inputs to the network design calculations were the operating pressure and temperature of the pipeline and the flow rate and physicochemical properties of the liquid/gas transported.

The cost of each network component (piping/ductwork) depends on the choice of material (e.g., stainless steel or carbon steel), transport distances or length (site-layout dependent), and the volumetric/mass flow rate of the fluid transported. Therefore, a two-way sensitivity of the direct cost associated with flue gas ductwork, solvent, and liquified CO_2 piping was performed as a function of ducting/piping lengths and flow rates. The materials, coating, and construction costs were computed as a component-specific cost factor per square meter of ductwork/piping (C_{f_comp}, in €/m^2) to simplify the capital cost estimation. Detailed information on the calculation procedure and the derivation of these component-specific cost factors can be found in Supplementary Materials S.4.

The total CAPEX of each network component[11] (C_{comp_capex}) is the product of the network component-specific cost factor (C_{f_comp}, in €/m^2) and the surface area of the ductwork or piping, as shown in Eq. (14), where Q_{comp} is the volumetric flow rate of gas/liquid transported (m^3/h), v_{comp} is the assumed gas/liquid velocity (m/s), L_{comp} is the length (m), and M_{comp} is the additional margin (20 %) assumed for estimated component lengths. Based on the site layout of the process plant and the merit order for space utilization (described in Section 3.5.1.2), the placement of decarbonization equipment was determined, from which the ductwork and pipeline routes and their corresponding lengths were estimated from aerial images of the site layout. Finally, the contribution of the local CO_2 transportation network to the total cost of retrofitability was calculated as the ratio of the total annualized cost of CO_2 interconnections[11] to the absolute amount of CO_2 captured or avoided, as shown in Eq. (15).

$$C_{comp\_capex} = \left(2\pi \sqrt{\frac{(Q_{comp}/v_{comp})}{\pi}} \cdot (L_{comp} \cdot M_{comp}) \right) \cdot C_{f\_comp} \ [€] \quad (14)$$

$$C_{netw} = \frac{((C_{fg} + C_{solv} + C_{CO2,liq})/ANF)}{\text{Total annual } CO_2 \text{ captured or avoided}} \left[\frac{€}{tCO_2} \right] \quad (15)$$

3.5.3. Cost of forced downtime

The cost of forced downtime was quantified as lost revenue (€) corresponding to the time a process plant is shut down, assuming that integration of decarbonization technologies renders the host process plant non-operational beyond the timeframe of the scheduled maintenance shutdown. Depending on the year of operation and the process industry, this timeframe could last up to two to four weeks in a regular year and one to three months in a turnaround year. Given that it is rather challenging to foresee commissioning delays, an informed early-stage assessment can be performed with a sensitivity analysis on the lost revenue incurred due to forced downtime, which was accounted as CAPEX during the construction of the decarbonization technology.

$$C_{FD} = \frac{\text{Annualized lost revenue due to forced downtime}}{\text{Total annual } CO_2 \text{ capture or avoided}} \left[\frac{€}{tCO_2} \right] \quad (16)$$

The specific cost of forced downtime (C_{FD}), shown in Eq. (16), was calculated as the ratio of annualized lost revenue, dependent on the duration of forced downtime, to the absolute amount of CO_2 captured/avoided during the decarbonized operation of the plant. The total annual revenue, calculated pro rata, was assumed to be distributed evenly over the number of operational months in a regular year. Here, the annualization factor was calculated based on the assumed economic lifetime of the decarbonization technology.

3.5.4. Cost of premature decommissioning (lock-in effect)

The lock-in effect of the decarbonization pathway, with its host process plant, is demonstrated with the capital recovery factory applied to its total capital requirement, as shown in Eq. (17). Here, the operational lifetime of the decarbonization technology (DT_{OLT}) was assumed to be equal to the residual lifetime of the decarbonized process plant (where DT_{OLT}<DT_{ELT}), to obtain the cost of premature decommissioning (C_{PD_total}). The contribution of premature decommissioning costs (C_{PD_cont}) to the cost of retrofitability (C_{COR}) was calculated as the difference between the capture and avoidance cost estimates with and without the cost of premature decommissioning), as shown in Eq. (18). A DT with the possibility of operating as a stand-alone process plant that is not locked into its host process plant was assumed to have an operational lifetime equal to its design lifetime (DT_{OLT}=DT_{ELT}). A sensitivity analysis illustrates how capture and avoidance costs escalate with a delay in installing and deploying decarbonization technologies that tend to be locked into their host plant.

$$C_{PD_{total}} = \frac{TCR \cdot \{ i(1+i)^{DT_{OLT}} / \{(1+i)^{DT_{OLT}} - 1\}\} + OPEX_{total}}{\text{Total annual } CO_2 \text{ capture or avoided}} \left[\frac{€}{tCO_2} \right] \quad (17)$$

$$C_{PD_{cont}} = C_{PD\_total} - (\text{CAP or CAC}) \left[\frac{€}{tCO_2} \right] \quad (18)$$

3.5.5. Cost of retrofitability

The cost of retrofitability (C_{COR}) is the sum of all the quantified site-specific cost factors (Sections 3.5.1–3.5.4), as shown in Eq. (19), which excludes the technical cost of CO_2 capture and avoidance from the s-TEA method. With this, the site-specific cost of avoidance ($CAC_{site\text{-}specific}$) was calculated as the sum of the cost of retrofitability ($C_{COR,avoided}$) to the baseline avoidance cost estimates from the s-TEA method (CAC, see Eq. (6)) respectively, as shown in Eq. (20).

$$\text{Cost of retrofitability } (C_{COR}) = C_{OC} + C_{netw} + C_{FD} + C_{PD\_} \left[\frac{€}{tCO_2} \right] \quad (19)$$

$$\text{Site} - \text{specific cost of } CO_2 \text{ avoided } (CAC_{site-specific}) = CAC + C_{COR,avoided} \left[\frac{€}{tCO_{2,avo}} \right] \quad (20)$$

3.5.6. Emissions intensity and cost of energy supply options

A two-way sensitivity analysis of indirect CO_2 emissions was performed assuming the ranges 0–300 gCO_2/kWh and 0–55.8 gCO_2/MJ (~200.9 gCO_2/kWh) for electricity and steam, respectively. The lower

[11] The subscript 'comp' stands for the network components considered in this work, that are subscripted as follows – flue gas ductwork ('fg'), solvent piping ('solv') and liquid CO2 piping ('CO2,liq').

Table 4
Calculation and plotting method on diagnostics diagram.

Site-specific factors	Calculation method
Quantitative factors	Normalized to the highest value within each quantitative factor, resulting in a maximum value of 1 for all factors
Qualitative factors	Based on the retrofitability assessment matrix (Supplementary Materials S.5), the median values are plotted on the diagnostics diagram. Interquartile ranges are presented in Supplementary Materials S.5.1
Sensitivity parameters	Compared based on their respective percentage change to the base value (e.g., fuel price), which is normalized with the technology with higher sensitivity to the base value.

limits of both ranges indicate an optimistic scenario with the lowest possible indirect CO_2 emissions assuming consumption of renewable electricity (at 0 gCO_2/kWh) on-site. The upper limits of grid emissions intensity were comparable to the emissions intensity in EU-27.[12] Similarly, the emissions intensity range of steam supply options was assumed to range from electric steam boilers (operated with renewable electricity) or recovered excess heat from industrial processes (at 0 gCO2/kWh) to NG-fired steam boilers (or dedicated NG boilers installed along with Post-CCS plant), with an equivalent emissions intensity as natural gas. A boiler efficiency of 90 % was assumed for cases where additional steam is required. Subsequently, a two-way sensitivity analysis of CO_2 avoidance costs (s-TEA estimates) was evaluated for varying energy supply (steam and electricity) costs (+/- 50 %) from the baseline natural gas and electricity price (see Table 2), resulting in an energy price range of 10–35 €/MWh (~3–9 €/GJ), and 30–90 €/MWh, respectively.

3.6. Qualitative site-specific factors

3.6.1. Retrofitability assessment

A qualitative retrofitability assessment, addressing operability and technical implementation issues adapted from Marton et al. (2020) and Voldsund et al. (2019), incorporating elements from the pedigree analysis[13] (Roussanaly et al., 2021; van der Spek et al., 2017a), was performed to assess the qualitative site and technology-specific cost factors of the case study plant. The qualitative assessment involved expert elicitation on the site-specific factors and their perception of the level of impact a certain decarbonization technology is expected to have on the host process plant. Each site-specific qualitative factor is rated on a 0–1 impact score. A score of 1 indicates that the evaluated factor has a higher overall impact on perceived risks and unforeseen costs, while a score of 0 indicates no impact on the host plant. Based on this, a retrofitability assessment matrix (see Table 4) was introduced with generalized definitions for each qualitative factor that applies to any process plant. The retrofitability assessment was conducted with a group consisting mainly of industry experts.[14] The interquartile ranges highlighting the degree of agreement or disagreement among the evaluators regarding the retrofitability of a decarbonization technology at a specific process plant are presented in Supplementary Material S.5.1. The median of all scores given by evaluators for each quantitative factor is plotted on a diagnostic diagram (see Section 3.6.2).

[12] 289–302 gCO2/kWh during the year 2017–2018 (European Environment Agency, 2023).

[13] The pedigree analysis uses a pedigree matrix which translates qualitative expert judgement of parameter, data and methods used into numerical strength scores (listed as rows), with problem-specific criteria (listed as columns) along with linguistically description within each cell, to aid the scoring process. More information on pedigree analysis can be found elsewhere (Roussanaly et al., 2021; van der Spek et al., 2016, 2017b).

[14] As per Knol et al. (2010), a minimum of six reviewers with the appropriate expertise is recommended to ensure the robustness of expert elicitation. In this study, four participants, consisting of three industry experts, were deemed sufficient to help minimize intra-expert heterogeneity, given their extensive site-level knowledge and direct experience with retrofitability in this field.

Table 5
Steam cracker plant data (Borealis AB, 2021; 2019).

Parameter	Units	Value
Flue gases composition		
H_2O	vol.%	> 20
CO_2	vol.%	< 8
N_2	vol.%	< 70
O_2	vol.%	< 2
Source of CO_2 emissions in the flue gas		
Cracker furnaces (~85 %)	kt/a	552.9
NG-fired steam boilers (~15 %)	kt/a	97.7
Total annual CO_2 emissions	kt/a	650.6
Temperature	°C	160
Product output (approx.)		
Ethylene	kt/a	647
Propylene	kt/a	133
Others[a]	kt/a	477

[a] An aggregated number for other products is presented here due to confidentiality. This number comprises raw steam cracked naphtha, C4-product, fuel gas, and hydrogen sold as products.

3.6.2. Diagnostics diagram

The results of the quantified site-specific factors, sensitivity analysis, and the retrofitability assessment matrix were visualized on a spider plot called the diagnostic diagram to present a holistic comparison between decarbonization technologies. A spider plot was chosen because each site-specific factor is not directly comparable with one another nor individually the primary determinants in the selection of the cost-optimal decarbonization technology. No weighting factor was assumed in this work. However, weighting factors could be assigned to the individual qualitative site-specific factors deemed important for other sites. Table 4 describes the calculation method behind plotting the site-specific factors on the diagnostic diagram. The decarbonization alternative with the greater spread on the spider plot indicates a suboptimal choice compared to the other decarbonization options plotted on the spider plot, considering their site-specific quantitative and qualitative factors and sensitivity to energy prices.

4. Case study – Steam cracker plant

The case study was based on a steam cracker plant located on the west coast of Sweden, consisting of 8 cracking furnaces that crack ethane and other mixed hydrocarbon feedstocks corresponding to an annual production capacity of up to 640 kt ethylene and 200 kt propylene (Borealis AB, 2021). Table 5 lists relevant plant data for the steam cracker plant. The cracker plant emits roughly 650 $ktCO_2$ annually, of which the cracker furnaces contribute 80–85 %, the remaining emissions coming from three natural gas-fired steam boilers (12–16 %) and flaring (1–3 %).

Fig. 6 illustrates the main material flows in a steam cracker plant and the decarbonization pathways considered in this work (see Section 3.2). The rationale for selecting these technologically mature decarbonization pathways and their implications on the steam cracker plant are discussed further in Supplementary Material S.1.1. As shown in Fig. 6a, fuel gases (50 vol. % CH_4 and 50 vol.% H_2) recovered from the cracked product gas are the main fuel used in the cracker furnaces to provide energy for the endothermal cracking reaction. In the Post-CCS pathway (see

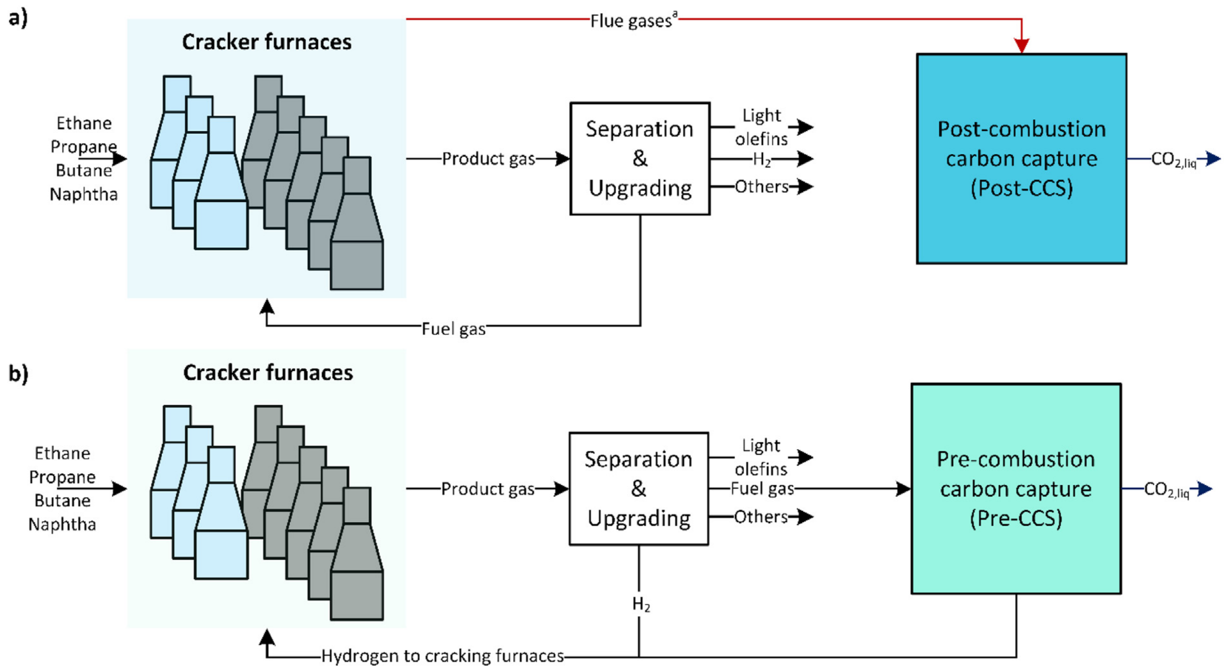

Fig. 6. Overview of the main material flows in a steam cracker plant with (a) post-combustion (Post-CCS) and (b) pre-combustion (Pre-CCS) decarbonization pathways. [a]Flue gases include total plant CO_2 emissions. In Pre-CCS, CO_2 emissions from furnaces are entirely avoided; however, CO_2 emissions from NG-fired steam boilers remain (not shown in the Figure). Note that the output streams for both pathways is liquified CO_2 at liquid CO_2 transport specifications (−26.5 °C, 15 barg, based on Northern Lights (2023)).

Fig. 6a), the CO_2 from the flue gases is captured using a benchmark amine-based solvent (monoethanolamine) CO_2 capture plant with an assumed capture rate of 90 %, followed by compression and liquefaction to sea-transportation specifications (Northern Lights, 2023).

In contrast, the Pre-CCS pathway entails valorizing methane-rich fuel gas (previously used as fuel for cracker furnaces) via steam-methane reforming to produce hydrogen, which is thereafter used as primary cracker fuel, as shown in Fig. 6b. The CO_2 generated from the steam-methane reforming reactions ends up in the tail gas (mainly containing CO_2, H_2, CH_4, and CO) of the hydrogen separation and purification units, which are oxidized with catalytic incinerators to obtain a pure gaseous CO_2 stream, prior to CO_2 liquefaction plant. The scope of decarbonization on-site was limited to avoiding CO_2 emissions from the cracker furnaces, with unchanged production capacity in both pathways. Therefore, at a CO_2 capture rate of 90 % from the flue gas at the stack, the Post-CCS process captures roughly 585.5 kt/a, capturing approximately 5 % more CO_2 than the total cracker furnace emissions (552.9 kt/a). In contrast, the Pre-CCS process with hydrogen-firing in the cracker furnaces, results in 100 % avoidance of CO_2 emissions associated with the cracker furnaces. However, the CO_2 emissions associated with the steam boilers remain.

4.1. Assumptions for the case study

Table 6 summarizes the assumptions for the aforementioned site-specific factors and estimated values from the case study plant.

4.1.1. Site-layout

Based on the existing site-layout diagram of the case study plant, different plant sections were zoned using aerial image of the case study site (see Supplementary Material S.6) and the modified onion-diagram (shown in Fig. 4a) The total areas within each plant section were then quantified. Subsequently, available space within each plant section was identified and classified based on the merit order for space utilization, described in Table 3, for the deployment of decarbonization technologies at the case study plant. Based on the available space within plant boundaries and the estimated total space required for the decarbonization technology, major equipment was placed following the merit order of space utilization in consolidated or fragmented configurations. Next, the interconnections required to transport CO_2 from the emissions point source to the plant fence were determined, providing approximate ducting and piping lengths.

4.1.2. Space-value graph

The annual average price for each multi-product steam cracker plant product was used to calculate its total annual revenue for the reported annual product output listed in Table 5. The linear and non-linear SV functions for the case study steam cracker plant were used to obtain an opportunity cost range. The gradient of the non-linear SV function (VF_{nl}) depends on the existing assets in the categorized plant sections and the perception of the installation complexity of decarbonization equipment. For example, in a typical steam cracker plant, several redundant units, such as tanks with larger physical footprints, are expected to be located further away from the cracker furnaces, which typically have relatively small footprints. Therefore, an exponential curve with a moderate rate of growth that better represents the case study plant was assumed.

4.1.3. Forced downtime

The case study plant has scheduled annual maintenance shutdowns, typically lasting one month. Its longer scheduled shutdowns, or turnarounds, last for about three months and occur every six years. No technology-specific forced downtime was assumed based on their integration complexity. Instead, the cost of forced downtime was estimated for shutdown periods ranging from 1 to 11 months, where the upper-bound accounts for the one-month maintenance shutdown period during a regular year.

4.1.4. Pre-mature decommissioning

Steam cracker plants typically have a lifetime of 50–60 years, beyond which significant reinvestments or decommissioning is required. The average age of an steam cracker plant in the EU is approximately 40–45 years (Petrochemicals Europe, 2022). Thus, a residual lifetime of

Table 6
Summary of site-specific assumptions and estimated values for the case study plant.

	Units	Value	Comments/References
Products			
Ethylene	€/t	1071	Assumed average price (Penpet Petrochemical, 2023a)
Propylene	€/t	1044	Assumed average price (Penpet Petrochemical, 2023b)
Raw C4 product	€/t	935	Assumed average price (Argus, 2023)
Raw steam-cracked naphtha	€/t	800	Assumed average price (Statista, 2023a)
Hydrogen product	€/t	1100	Assumed 1.1 €/kgH_2 (IEA, 2020)
Fuel gas	€/t	262	Estimated based on the composition of the fuel gas
Space value functions			
VF_l	€/m^2	5807.77	Estimated using Eq. (2)
VF_{nl}	€/m^2	$3.6084e^{3e-05x}$	Estimated coefficients for the non-linear function Eq. (9), based on assets in different plant sections, categorized as shown in Fig. 4a.
CO_2 emissions intensity			
Electricity	gCO_2/kWh	50	Assumed Swedish average grid carbon intensity (Bastos et al., 2024)
Natural gas	gCO_2/kWh	200.95	55.82 gCO_2/MJ_{NG} excluding distribution emissions (European Commission, 2017)
Categorized available space	–	Estimated area	Numbered spaces in Figure S.7
Brownfield (Class-I)	m^2	11,202	1–3
Brownfield (Class-II)	m^2	8519	4–9
Greenfield	m^2	11,611	10, 11
Overview of equipment considered in the TEA methods–	–		Detailed equipment list is provided in Supplementary Material S.3
Standardized TEA method	–		CO_2 capture, purification, and liquefaction units
Site-specific TEA method	–		CO_2 capture, purification, and liquefaction units, on-site CO_2 transportation
Equipment costs not included in both TEA methods	–		On-site storage, off-site transportation and storage costs, replacement of burners, revamping of fuel gas system
Default assumptions used in the estimation of total cost of retrofitability in Fig. 8	–	**Post-CCS**	**Pre-CCS**
Average EU-ETS price assumed for estimating C_{OC}	€/tCO_2	75	75
Assumed duration of forced downtime, C_{FD}	Months	1	1
Assumed decommissioning year of the steam cracker plant, Y_{ey}		2045	2045
Assumed CCS deployment year synchronized with turnaround year, Y'_{dy}		2033	2033
Corresponding operational lifetime (DT_{OLT}) due to pre-mature decommissioning [a]		12[b]	20[c]
Opportunity cost (OC)			Averaged estimates of SF_{min}–SF_{max} (m^2) at linear SV function, corresponding to max lost annual revenue used to display C_{OC} values in Fig.8.

[a] Note that decarbonization technologies have a design lifetime of 20 years. The lower bound corresponds to a reduced economic lifetime due to the decommissioning of the case study plant in 2045.

[b] Based on Y'_{dy}. Utilization of the full design lifetime of the Post-CCS plant is only possible with reinvestment in the case study plant to extend its lifetime until the year 2053.

[c] No technology lock-effect in the Pre-CCS process; therefore, it is able to operate as a standalone plant beyond Y_{ey}.

22–28 years from the current year was assumed, where the lower bound corresponded to the net-zero CO_2 emissions target year of 2045. The upper bound, corresponding to the year 2053, represents the extended plant lifetime with significant reinvestments to continue operating with its existing assets. The Post-CCS pathway was assumed to be linked to the residual lifetime of the case study plant, owing to its design being inherently linked to the flue gas properties of the case study plant. In addition, it was assumed that the installed equipment cannot be salvaged, therefore having no residual economic lifetime beyond the lifetime of the case study plant. In contrast, the Pre-CCS pathway was assumed to serve as a stand-alone plant beyond the lifetime of the case study plant, as it has access to the natural gas grid, which could be utilized for low-carbon hydrogen production, therefore, utilizing its full design lifetime of 20 years. Considering construction lead times and the current lack of incentives (UNEP, 2023) to decarbonize before 2030, it was assumed that the CCS deployment would occur in the turnaround year scheduled for 2033.

4.1.5. Site-energy system

Three natural gas-fired steam boilers currently operate at the case study plant, producing high-pressure steam (450 °C, 85 bar) (Hackl and Harvey, 2013). Furthermore, the excess heat from the flue gas (below ~160 °C) is not currently recovered. It was assumed that any energy savings from heat recovery from newly installed decarbonization equipment would lead to decreased natural gas firing in the existing boilers, thus indirectly avoiding direct CO_2 emissions on-site. In the Pre-CCS process, the hydrogen demand was calculated based on the current fired duty for all cracker furnaces that combust fuel gas. This results in a pure hydrogen demand of 12 t/h (corresponding to a cracker-fired duty of 400 MW), of which 3.7 t/h is recovered internally from the existing fuel gas system. The remaining hydrogen is produced via auto-thermal reforming of methane recovered from the existing fuel gas system. Finally, heat integration was performed to estimate the steam balances on-site and the corresponding influence on the indirect CO_2 emissions from the considered decarbonization pathway.

Table 7
Estimated technology-specific local CO_2 interconnection lengths based on CO_2 network routing considering site-layout constraints.

CO_2 network components	Unit	Decarbonization pathways	
		Post-CCS	Pre-CCS
Flue gas/Gas ductwork	m	300.5[a]	360[b]
Solvent piping	m	360[b]	0
Liq. CO_2 pipeline	m	1071.3[a]	1071.3[a]

[a] Estimated lengths based on the CO_2 network routing (Supplementary Materials S.9).
[b] Assumed lengths based on the total available area of the plant section where the equipment is placed (Supplementary Material S.6).

4.2. Identified space on-site and corresponding CO_2 interconnections

Figure S.7 in Supplementary Materials S.8 presents an aerial image of the case study plant, extracted from Google Maps (2023), highlighting the identified space on-site categorized as either brownfield or greenfield areas. These areas are color-coded based on the merit order for space utilization (see Table 3). Table 6 lists the total area in each category of space available on site. The area of each defined region was estimated using tools offered by ArcGIS and Google Maps (2023). These identified spaces were first used to determine where the decarbonization technologies could be installed and then determine the optimal network route within the plant boundary to estimate the lengths of ductwork and piping for each decarbonization pathway. These lengths are then used to determine the site-layout-dependent interconnection costs, as described in Section 3.5.2. Based on the identified space on-site (Figure S.7) and the placement of decarbonization equipment, representative CO_2 network routings for the decarbonization pathways were determined for the case study plant. More information is provided in Supplementary Material S.9. The tentative CO_2 network routes (Figure S.8) confirm the technology-specific disparity in the local CO_2 infrastructure requirements to transport CO_2 from the emissions point source to the host plant's fence. While the lengths of liquified CO_2 piping were comparable for the two pathways, the lengths of required solvent piping, flue gas ductwork, and fuel gas piping/ductwork requirements differ for the Post-CCS and Pre-CCS pathways. Table 7 shows the estimated length for each network component, with a margin of 20 %, based on technology-specific CO_2 network routing determined based on site-layout constraints.

4.3. Scenario analyses

The impact of site-layout constraints on the design and placement choices of the decarbonization technology is illustrated with scenarios accounting for the estimated spatial footprint from the SF tool (see Section 3.5.1.1) and the identified available space within the case study plant, shown in Figure S.7. Here, consolidated design configurations were chosen when the estimated SF of the decarbonization pathway was less than the total available space within Brownfield-I areas (based on Table 3). A fragmented design configuration was chosen when the total available space within Brownfield-I areas was deemed insufficient to accommodate a consolidated design configuration, which inherently assumes the removal of existing assets in Brownfield-II areas. Four decarbonization scenarios (DS) were investigated, two for each decarbonization pathway based on the estimated minimum and maximum bounds of their respective SF range (see Section 5.3.1).

5. Results

The results are presented in three parts. First, the impact of the cost of retrofitability (or the sum of all site-specific cost factors) on the baseline cost estimates from the s-TEA method is given for the case study plant.

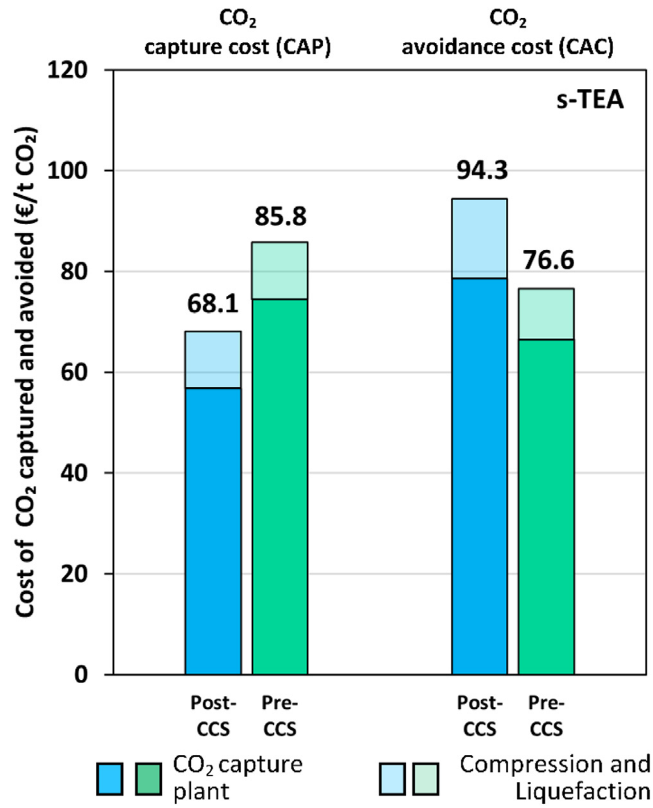

Fig. 7. Estimated cost of CO_2 capture and avoidance, which includes the CO_2 capture plant (darker shade) and compression and liquefaction units (lighter shade). Note that CO_2 avoidance cost estimates assume a CO_2 emissions intensity of 50 gCO_2/kWh and 200 gCO_2/kWh for electricity and steam supply on-site.

Second, the impact of each site-specific factor on the cost of retrofitability is presented, along with case-study-specific results. Third, considering the site-layout constraints of the case study plant, the resulting deployment scenarios and their cost estimates are presented. Finally, using the retrofitability assessment matrix, the diagnostics diagram is presented for enhanced comparative indication of the optimal decarbonization pathway.

5.1. CO_2 capture and avoidance cost escalation with site-specific cost factors

5.1.1. Baseline cost estimate from standardized techno-economic analysis (s-TEA)

Fig. 7 shows the estimated cost of captured and avoided CO_2 for the Post-CCS and Pre-CCS decarbonization pathways estimated using the s-TEA method. The capture and avoidance cost estimates are presented for the capture plant and the CO_2 liquefaction plant, whereas transportation and storage are excluded.

The CO_2 capture and avoidance costs for the case study plant were estimated to be 68.1–85.8 €/$tCO_{2,cap}$ and 76.6–94.3 €/$tCO_{2,avo}$. Both capture and avoidance costs lie in a narrow range, with a relative difference of roughly 20–23 % between the two decarbonization technologies. These estimated ranges are well within the accuracy range of the applied hybrid bottom-up/top-down cost estimation method,[15] i.e., it is not possible to draw conclusions about the cost-optimal solution using the s-TEA approach.

[15] Typically considered as Class 4 estimate with an accuracy range between −15% to +50% (Christensen and Burton, 2005).

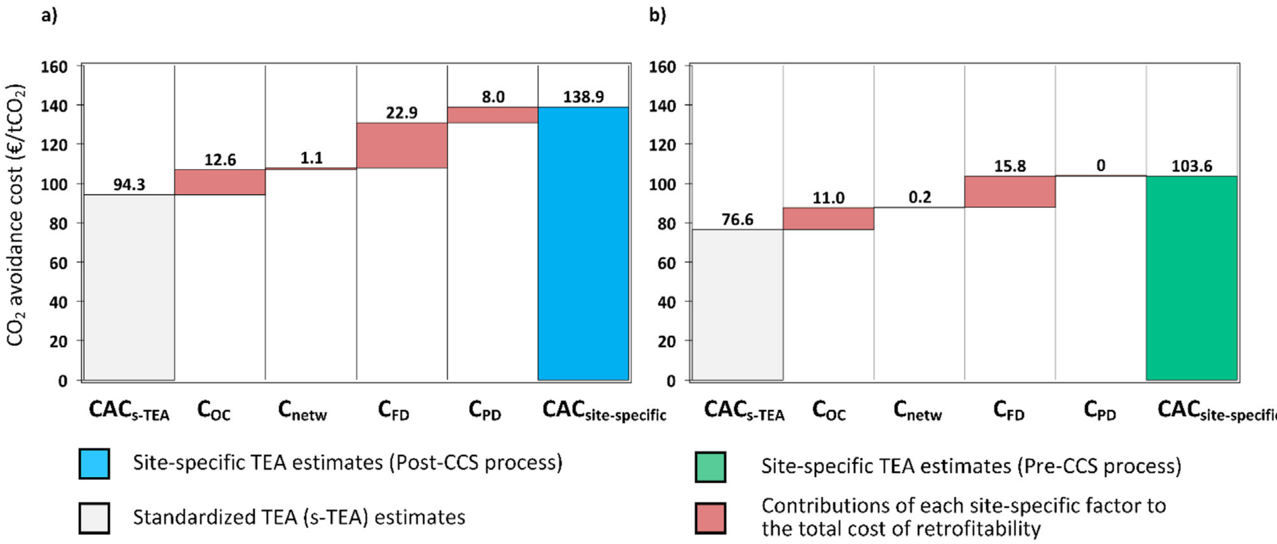

Fig. 8. Site-specific cost of CO_2 avoidance for (a) Post-CCS and (b) Pre-CCS pathways (see descriptions in Section 4). Note that the average value of opportunity costs (estimated for different SV functions) was taken here, where the default assumptions are—EU-ETS price (75€/tCO_2), forced downtime (1 month), operational lifetimes of 12 and 20 years for Post-CCS and Pre-CCS respectively (Table 6). See Nomenclature for figure abbreviations.

Furthermore, technology comparisons purely based on specific capture costs could be misleading, as significantly more CO_2 is captured via the Post-CCS process (585.5 kt/a) compared to the Pre-CCS process (548.6 kt/a). Also, efficiency losses are inherently included in capture cost estimates, which implies that with the same level of investment in a Post-CCS plant, an inefficient process plant with higher fuel consumption would result in higher absolute CO_2 emissions that would, in turn, yield a lower capture cost than a process plant with efficient processes. In the context of a steam cracker plant, a fuel switch from H_2-rich fuel gases to a C-rich fuel could, in turn, yield lower capture costs for the same upfront investment in a Post-CCS plant.

In the remainder of the paper, the performance of the two decarbonization processes is presented in terms of CO_2 avoidance cost, accounting for their indirect CO_2 emissions to drive the capture processes. Based on the assumptions in Section 4.1, the avoided CO_2 emissions were estimated to be approximately 423 ktCO_2 and 614 ktCO_2 for the Post-CCS and Pre-CCS processes, respectively, corresponding to a relative difference between the two decarbonization alternatives of 36.5 % (see Supplementary Material S.10). The sensitivity of the equivalent CO_2 emissions avoided (AC_{eq}) and associated costs with varying emission intensity for energy supply are presented in Section 5.2.

5.1.2. Site-specific cost of CO_2 capture and avoidance

Fig. 8 shows the baseline avoidance cost estimates from the s-TEA method, indicated with grey- bars, to which site-specific cost factors (indicated with red solid floating bars), together representing the total cost of retrofitability, are added to obtain the site-specific cost of avoidance. Note that cost escalations shown in Fig. 8 are estimated with the baseline site-specific assumptions (see Table 6) to illustrate the differences at a conservative level. However, the full scope of expected cost escalation beyond the baseline site-specific assumptions is demonstrated in Section 5.4.1, where the impact and contribution of each site-specific factor to the technology-specific cost of retrofitability is evaluated.

In general, of all the quantified site-specific factors, the forced downtime (assumed to be one month), followed by the opportunity costs associated with the spatial footprint of the CCS process, were the most significant contributors to the cost of retrofitability. Accounting for avoided CO_2 emissions, the cost difference between the two decarbonization alternatives widens significantly, as shown in Fig. 8a–b. The site-specific avoidance costs increase to 139 €/$tCO_{2,avo}$ and 104 €/$tCO_{2,avo,}$ from the baseline estimates of 94 €/$tCO_{2,avo}$ and 76 €/tCO_2 from the s-TEA method for Post-CCS and Pre-CCS, respectively (relative increases of 47 % and 35 % for Post-CCS and Pre-CCS, respectively). This is due to technology-specific characteristics e.g., required spatial footprint, lock-in effect, and installation complexity, which were further accentuated by site-level constraints, such as site-layout constraints resulting in differing opportunity costs and emissions intensity of site-level energy supply.

5.2. Sensitivity of findings to emissions intensity and the corresponding cost of energy supply options

5.2.1. Impact of emissions intensity of energy supply

Fig. 9 shows the sensitivity of equivalent CO_2 avoided (AC_{eq}, Eq. (3)) to the emissions or carbon intensity of electricity and steam consumed on-site by the Post-CCS (Fig. 9a) and Pre-CCS process (Fig. 9b). The X-axis represents the carbon intensity of steam generation on-site (CI_{steam}), and the Y-axis represents the emissions intensity of the purchased grid electricity ($CI_{electricity}$). The origin point (0 gCO_2/MJ_{steam}, 0 $gCO_2/kWh_{electricity}$) represents a future site-energy system scenario where renewable electricity is used for both electricity and steam generation requirements. Conversely, the maxima (at 55 gCO_2/MJ_{steam}, 300 $gCO_2/kWh_{electricity}$) represent the existing site-energy system scenario where electricity and steam requirements in the decarbonization technology are met with grid electricity with the current average grid emissions intensity in EU-27 and on-site natural gas boilers. The color bar represents the AC_{eq}, where the limits were set by the highest (85 %) and lowest (55 %) possible CO_2 avoidance estimated for Post-CCS and Pre-CCS processes, respectively.

The equivalent CO_2 emissions avoidance was estimated to range between 59 and 85 % and 83–96 % of unabated plant emissions for the Post-CCS and Pre-CCS processes, respectively. Fig. 9 shows that both processes are more sensitive to the emissions intensity of steam than the grid electricity CO_2 intensity. The effect of grid emissions intensity is similar in both processes, where lower CO_2 avoidance is achieved at higher values of emissions intensity of grid electricity. However, the impact is more pronounced for the Pre-CCS process due to the higher electricity consumption, as observed by the difference in gradient in Fig. 9b compared to Fig. 9a.

The Post-CCS process is a net consumer of heat and electricity. In contrast, the Pre-CCS process predominantly consumes electricity but releases significant amounts of excess heat at high temperatures that can be recovered and used for steam generation. This offsets a consider-

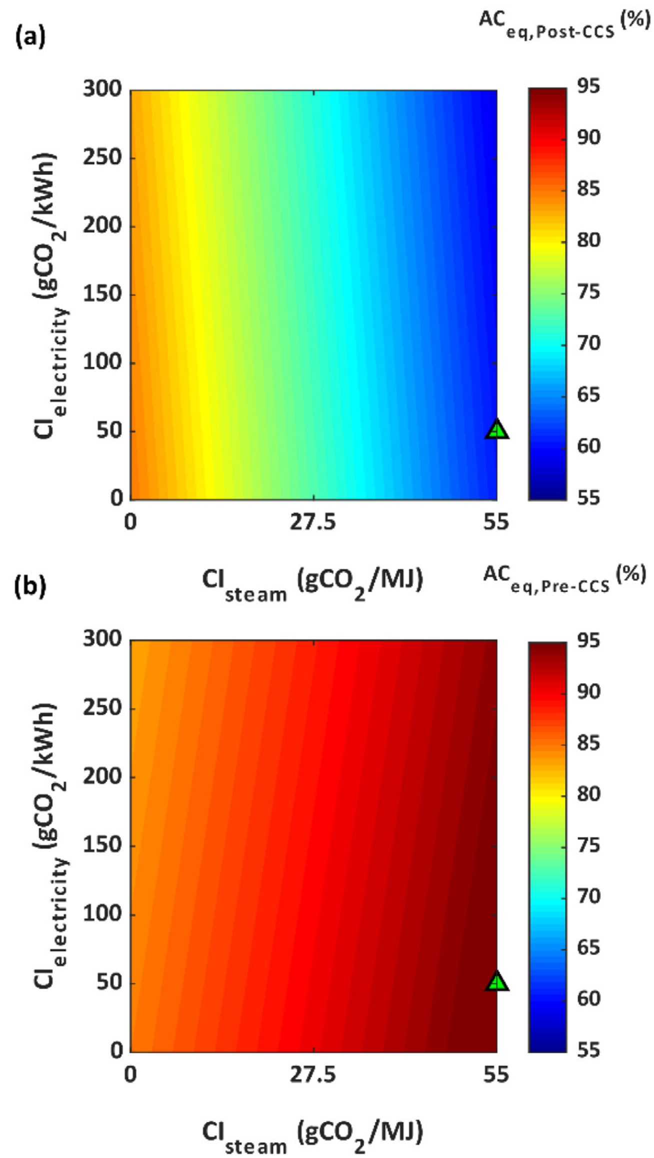

Fig. 9. Sensitivity of equivalent avoided CO_2 emissions (AC_{eq}) to the CO_2 emissions intensity of electricity (CI_{el}) and steam supply options (CI_{steam}), from a) Post-CCS process with a capture rate of 90 % and b) Pre-CCS. Green (Δ) markers indicate the CO_2 avoidance achieved at the case study plant with the baseline CO_2 emissions intensity assumptions for steam and electricity, as per Table 8.

able amount of on-site CO_2 emissions from the existing NG-fired steam boilers currently operated at the case study plant. Therefore, the effect of emissions intensity of steam generation is contrasting for the two processes due to steam consumption in Post-CCS and steam generation in Pre-CCS. For Pre-CCS, AC_{eq} decreases with a decreasing emissions intensity of steam (Fig. 9b) since the substitution of CO_2 emissions from NG-fired steam boilers is diminished. In existing site-energy systems with NG-fired steam boilers, significant CO_2 avoidance (AC_{eq} ~94 %) and operational cost savings are expected due to the substitution effect on the steam source.

In contrast, the Post-CCS process is expected to release recoverable excess heat at relatively low-temperature levels (2.09 MJ/kgCO_2, 47–86 °C (Kumar et al., 2023)), which does not have the same substitution effect. Increasing capture rates beyond 90 % in the Post-CCS process could marginally improve the AC_{eq}, although the extent of additional CO_2 avoidance would depend on the emissions intensity of the additional energy consumed. This additional energy could be provided by unrecovered excess heat[16] on-site. However, such measures would also subject the Post-CCS process to site-level heat supply variations[17] and their corresponding costs.

The Post-CCS process could improve the AC_{eq} by approximately 26 percentage points if the capture process is driven by renewable electricity. However, even with such conditions, the Post-CCS process attains a maximum AC_{eq} of 85 %, comparable to the minimum AC_{eq} obtained for the Pre-CCS process (83 %). It is worth noting that the Pre-CCS plant attains a maximum AC_{eq} of 96 % if operated with renewable electricity. Thus, Fig. 9 shows the inherent operational limitations of the Post-CCS process, where minimizing indirect CO_2 emissions through electrification of steam supply imposes a sub-optimal use of high-exergy electricity, leading to residual heat at lower temperature levels which cannot be used to substitute the current fossil-based energy consumption on-site. Contrastingly, the Pre-CCS process, which consumes high-exergy electricity, in turn, provides high-quality steam with heat recovery, which could be utilized to electrify existing process equipment directly or indirectly with electricity generation on-site or turbine-driven pumps and compressors, respectively.

5.2.2. *Impact of energy supply costs on CO_2 avoidance costs*

Fig. 10a-b shows the influence of energy supply costs on the cost of avoided CO_2 for the Post-CCS and Pre-CCS processes. The estimated CO_2 avoidance cost for the case study plant with the baseline energy cost assumptions (Table 2) is indicated with marker 'x' in Fig. 10. Note that sensitivity analyses in Fig. 10 are performed for baseline assumptions for energy supply emissions intensities (Section 3.5.6), corresponding to the marker 'Δ' in Fig. 9.

The estimated CO_2 avoidance costs for the Post-CCS and Pre-CCS process range between 72 and 134 €/t$CO_{2,avo,}$ and 48–87 €/tCO_{2avo}. Fig. 10 shows that the decarbonization technologies have a stronger sensitivity to price variations in the utility (steam or electricity) with the highest consumption rate. For example, the Post-CCS process is relatively sensitive to steam prices, whereas the Pre-CCS process is sensitive to electricity prices due to its higher electricity demands. However, the impact on CO_2 avoidance cost is more pronounced for the Post-CCS process than the Pre-CCS process due to its inherent limitations on achieving CO_2 avoidance (Fig. 9) at the same level of decarbonization at the cracker furnaces. In addition, a significant amount of on-site CO_2 emissions is offset via heat recovery in the Pre-CCS process, which implies the avoidance cost trends moved in a contrasting manner for both processes with varying steam prices.

The sensitivity analysis in Figs. 9 and 10 emphasizes the significant CO_2 avoidance possibilities at a lower avoidance cost with the Pre-CCS process, which offsets the higher upfront investment and increased reliance on external energy supply. The Post-CCS process offers independence from external energy supply as it depends primarily on energy supply from within the plant, considering additional steam demand is supplied from existing steam boilers. Nevertheless, due to the significant limitation on overall CO_2 avoidance achievable with the Post-CCS process, significantly higher CO_2 avoidance costs can be expected with the application of the Post-CCS process to decarbonize steam cracker furnaces. Options such as increasing capture rates beyond 90 % to minimize vented CO_2 from the absorber or electrification of steam generation utilities[18] are expected to result in CO_2 avoidance costs that are well beyond 120 €/t$CO_{2,avo}$ (the maximum estimated avoidance cost in Fig. 10a) in the Post-CCS process.

[16] Assuming an emissions intensity of 0 gCO2/kWh for recovered excess heat based on Biermann et al. (2022a).

[17] For example, temporal variations (Biermann et al., 2022a) or future decarbonization measures leading to increased or decreased availability of recoverable excess heat on-site (Wiertzema et al., 2020).

[18] Price of steam from electric steam boilers are expected to be 64.8/MWh (~18 €/GJ (Roussanaly et al., 2021)), roughly 85% higher than the X-axis limits in Fig. 10.

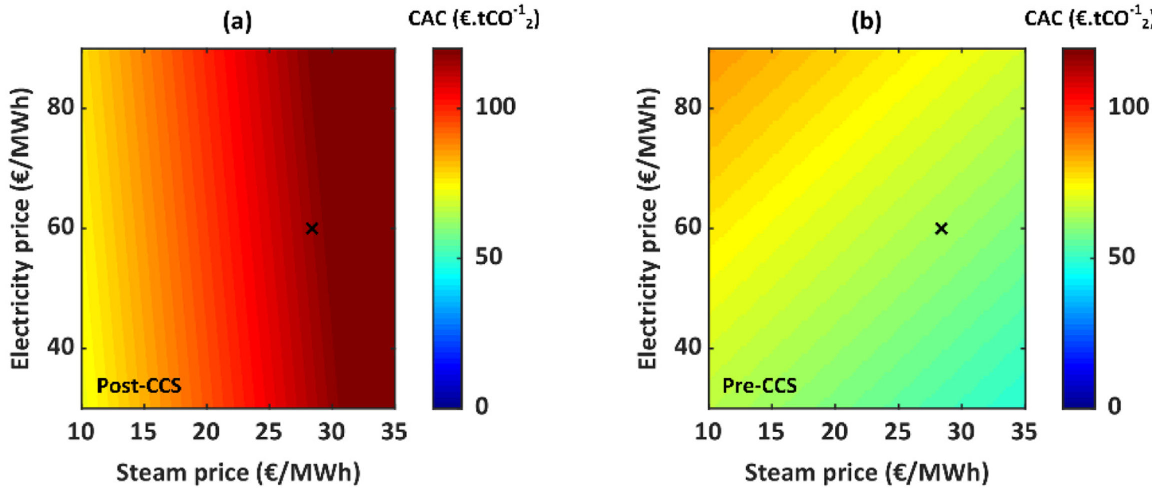

Fig. 10. Impact of energy supply costs on CO_2 avoidance costs (color bar). Marker (x) indicates the baseline cost assumptions of 60 €/MWh and 28.4 €/MWh for electricity and steam, respectively.

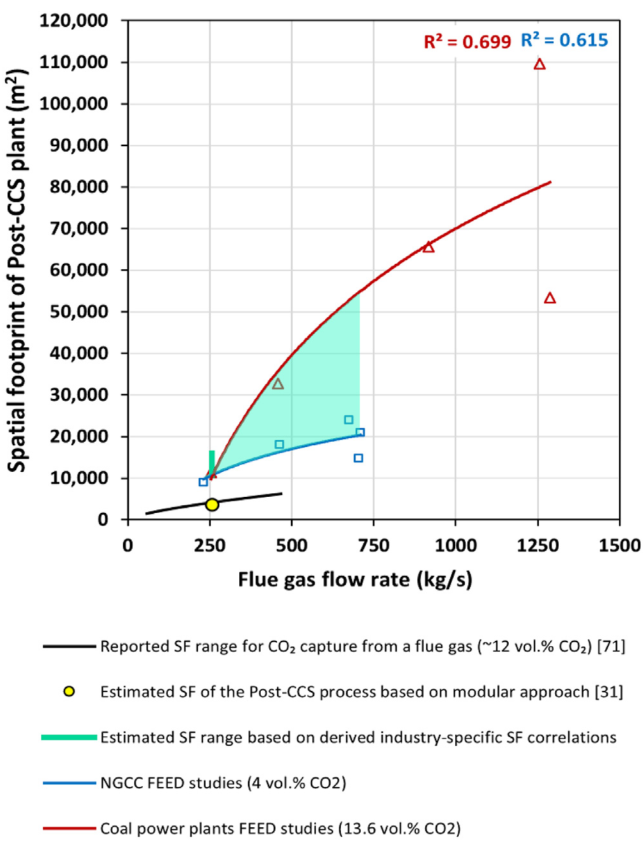

Fig. 11. Spatial footprint estimation tool developed based on reported spatial footprint of amine-based CO_2 capture plants in FEED studies for coal and natural gas-based power plants. The green-shaded region indicates the validity range of the tool.

5.3. Spatial footprint estimation

5.3.1. Spatial footprint requirements of the Post-CCS process

Fig. 11 plots the results from the spatial footprint (SF) estimation tool developed for the Post-CCS process, with FEED-derived SF correlations. The derived industry-specific correlations are indicated with red (coal) and blue (NGCC) solid curves. The solid black curve indicates the estimated SF footprint from the incumbent linear approach (Danish Energy Agency, 2021), while the yellow marker shows the estimated SF footprint of a Post-CCS plant using the modular approach, as per Berghout et al. (2015) and Blok and Nieuwlaar (2016). In Fig. 11, the overlap region between these two industry-specific correlations sets the validity range (shaded in green) based on CO_2 concentrations within 4–13.6 vol.% and a flue gas flow rate within 230–710 kg/s. As described in Section 3.5.1.1, only detailed FEED studies were considered in the SF estimation tool, which limited the number of data points available to derive these industry-specific correlations, which yielded a relatively moderate fit ranging roughly between 0.62–0.7.

The spatial footprint increases with increasing flue gas flow rates and is larger for coal power plants (13.6 vol.% CO_2) compared to the NGCC plants (4 vol% CO_2). This is inconsistent with the conventional notion that diluted flue gas streams require larger overall spatial footprints due to larger capture units, i.e., larger column diameters (assuming a maximum fixed column height). While this is true for the absorber and stripper columns in the Post-CCS plant, it was observed that the auxiliary units tend to be the main contributing factor to the space requirements. For example, flue gases from coal power plants tend to have higher SO_x contaminants that may require additional flue gas desulphurization units prior to the absorber (Preston et al., 2020; Robert and Brown, 2004), thereby increasing the physical footprint of the Post-CCS plant for coal plants. Site-specific characteristics, such as access to cooling water, tend to further influence the space requirements of the Post-CCS plant. FEED studies on CCS integration to inland coal-power plants, with limited access to cooling water, indicate that the installation of wet-air source coolers occupies roughly a third of the total space required by the Post-CCS plant (Bhown, 2022). These industry-specific aspects are typically not captured until advanced design stages involving engineering designs of the CCS plant incorporating site-layout constraints.

Comparison with incumbent SF estimation methods: In Fig. 11, the solid black line shows the estimated SF of amine-based CO_2 capture plants based on a reported SF range for a flue gas stream containing 12 % CO_2 by volume (Danish Energy Agency, 2021). The estimated SF value using the incumbent modular approach (Berghout et al., 2015) lay close to the reported linear scaling function (Danish Energy Agency, 2021), estimating roughly 4000 m^2 of area required to install all equipment associated with the Post-CCS pathway. Nonetheless, for varying flue gas flow rates, Fig. 11 confirms that the linear scaling approach (solid black line) and the modular approach (yellow marker) tend to neglect industry-specific attributes, resulting in a pronounced underestimation of the SF requirements of the Post-CCS plant at an early stage.

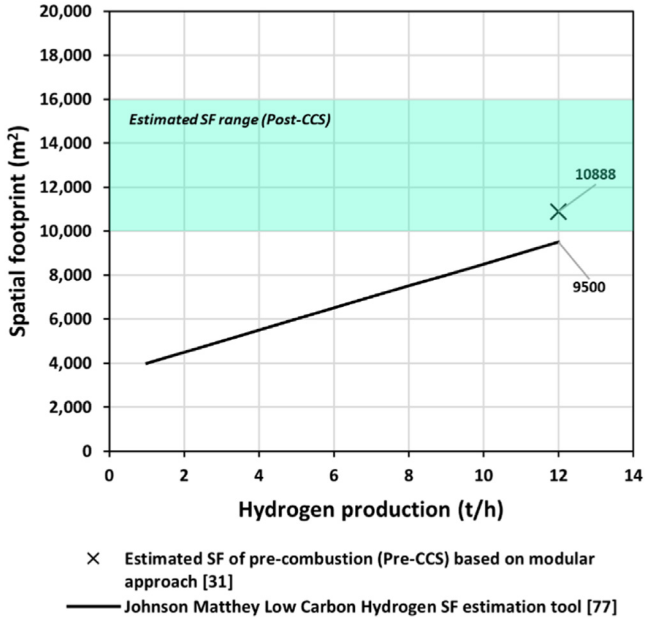

Fig. 12. Comparison of the estimated spatial footprint of Pre-CCS with the estimated SF range for Post-CCS decarbonization pathways (green solid vertical line, in Fig. 11) for the case study steam cracker plant.

Case study: The SF range for the Post-CCS plant was estimated to range between 10,000–16,000 m^2 (indicated with the green solid line in Fig. 11). The wide range encompasses uncertainty in the FEED-study-derived SF correlations. Nevertheless, considering the relatively low amounts of gas contaminants and access to cooling water at the case study plant compared to inland coal power plants, the physical footprint requirements of the Post-CCS plant applied to the steam cracker plant are expected to be close to the lower bound of the estimated SF range. The full range of the SF estimate was considered for comparison and sensitivity analyses, which is magnified and presented as a range (green-shaded region) in Fig. 12 for comparison with the Pre-CCS SF estimates. The SF estimates with a smaller range could be obtained if more CCS-related FEED studies with information on flue gas characteristics, CCS plant design, and area estimates were available.

5.3.2. Comparison of spatial footprint requirements of Post-CCS and Pre-CCS process

For a hydrogen demand of 12 t/h, the SF of the Pre-CCS process from the modular approach was estimated to require 10,888 m^2 of space at the case study site. Equipment-wise area estimates are provided in Supplementary Material S.3. The estimated SF of the Pre-CCS plant is plotted in Fig. 12 along with the SF estimated for the Post-CCS process and the Pre-CCS SF estimated with Johnson Matthey open-source estimator tool for the production of low-carbon hydrogen (French, 2020; Matthey, 2023). The Johnson Matthey estimates (black solid line) highlight the linear scaling of the Pre-CCS process related to the hydrogen production capacity.

The Pre-CCS spatial footprint estimated using the modular approach is in the same order of magnitude as the Johnson Matthey-based estimates with a relative percentage difference of less than 15 %. Comparing the two decarbonization pathways, the estimated range for the Pre-CCS process (9500–10,888m^2) lies close to the lower bound of the estimated range for the Post-CCS process. Fig. 12 highlights larger uncertainty in spatial requirements for the Post-CCS plant, which tends to require significantly larger space at the case study plant than the Pre-CCS process. The large range of uncertainty can be attributed to the limited amount of publicly available FEED studies with detailed SF estimates.

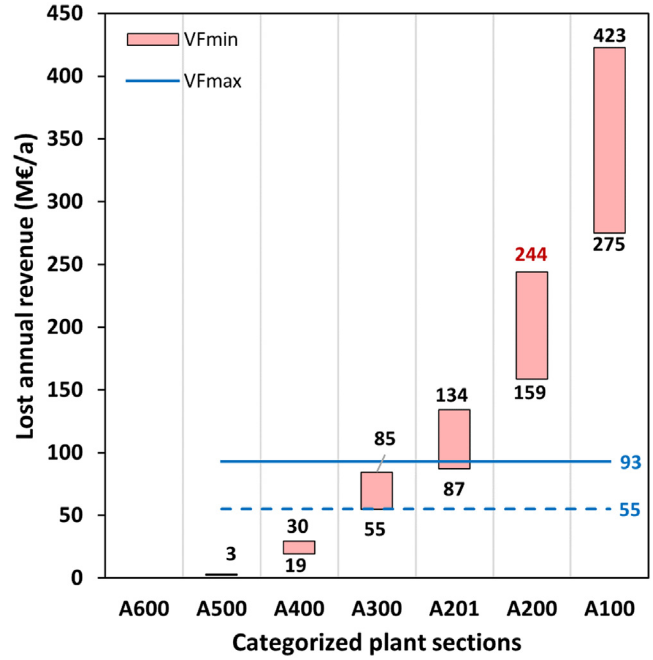

Fig. 13. Sensitivity of the estimated lost annual revenue as a function of placement of the decarbonization technology within different plant sections and the assumed SV function. The upper and lower bounds of the floating bars (VF_{nl}) and horizontal lines in blue (VF_l) correspond to the estimated maximum (16000m^2) and minimum (9500m^2) SF of the decarbonization pathways, respectively. See Supplementary Materials S.6 and nomenclature for categorized plant sections with respective area codes.

5.4. Site-specific cost estimates with variation in site-specific factors

This section presents sensitivity analyses of the investigated site-specific factors where site-specific factors are considered one-at-a-time, meaning that the contribution of each site-specific factor and the variation in cost estimates are assessed relative to the baseline cost estimates (see Fig. 7). For clarity, cost terminologies consistently used in this section are differentiated as follows— First, the individual contribution of each site-specific factor[19] are subscripted with their corresponding abbreviations (e.g., opportunity cost, C_{OC}). Second, the sum of a site-specific factor with the baseline capture and avoidance costs (in €/tCO_2, see Fig. 7) in Subsections 5.4.1 and 5.4.5 are indicated as individual factor-specific totals (e.g., C_{OC_total} or C_{PD_total}).

5.4.1. Cost of the spatial footprint of decarbonization technology

Fig. 13 shows the sensitivity of the estimated lost annual revenue range from the linear and non-linear SV function, accounting for the SF of the decarbonization technology and its placement within different plant sections. Therefore, in Fig. 13, the decarbonization technology-type and the site layout constraints, i.e., the lack of space at a particular plant section of the case study plant, are not considered.

Fig. 13 shows the lost annual revenue, with the linear (VF_l) SV function, which remains in a constant range between 55 and 93 M€/a, irrespective of where the decarbonization equipment is placed within the plant. In contrast, with the non-linear SV function (VF_{nl}), the lost annual revenue increases exponentially, as expected, from the outer to the inner layers of the modified onion diagram (see Fig. 4a). In Fig. 13, the lower and upper bound values for each VF at each plant section correspond to the estimated min/max SF of 9500–16000m^2 (See Section 5.3.2). Note that the upper-bound lost annual revenue estimated (with VF_{nl}) in the primary fractionation section (A200) is indicated in red to exemplify an

[19] Refer to Eqns. 12, 16,17,19 and 20.

Table 8
Deployment scenarios.

Decarbonization Pathways		Post-CCS		Pre-CCS	
Deployment Scenario		**DS-I**	**DS-II**	**DS-III**	**DS-IV**
Placement within the plant (Figure S.5)	Area	A201	A201, A300, A400	A201	A201
Installation Configuration	Unit	Consolidated	Fragmented	Consolidated	Consolidated
Estimated spatial footprint	m^2	10,605	15,975	9500	10,888
Lost annual revenue ($AR_{,loss,VFl}$–$AR_{,loss,VFnl}$)[a]	M€/a	61.6–124.1	92.8–109.5	55.2–114.1	63.2–126.5
Estimated (C_{OC_total})[b]	€/$tCO_{2,avo}$	89.3–112.7	93.9–110.6	64.3–93.6	65.4–95.4

[a] Lower and upper bound estimates in the lost annual range correspond to VF_l and VF_{nl}, space-value functions, respectively.
[b] Lower and upper bound estimates correspond to an EU-ETS permit price range of 0–225 €/tCO_2, averaged over the residual plant lifetime.

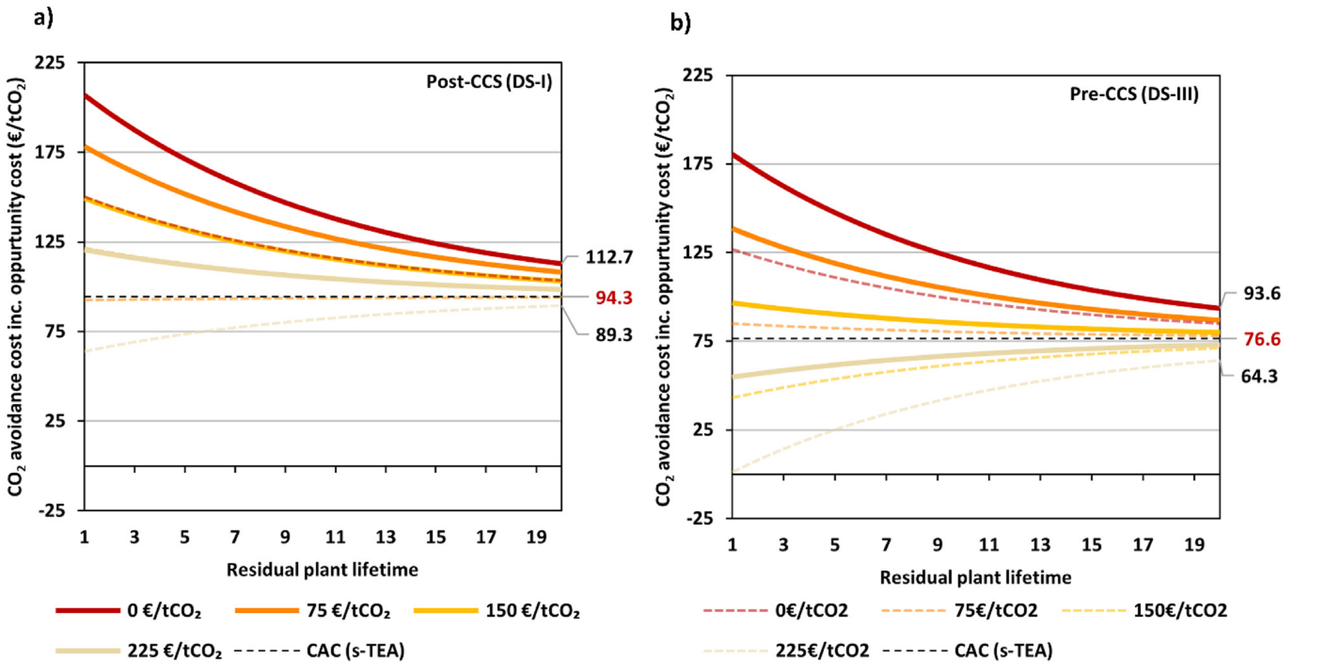

Fig. 14. CO_2 avoidance cost, including the opportunity cost of space available on-site for different deployment scenarios. Here, a wide range of annually averaged EU-ETS permit prices (0–225 €/tCO_2) were assumed for each year, which depreciates over the residual lifetime (20y) of the case study plant. Solid and dashed lines represent the maximum (VF_l) and minimum (VF_{nl}) space-value functions assumed for the case study plant. Black dashed lines denote CAC estimated from the s-TEA method.

impractical solution for the case study plant due to insufficient space within this plant section to accommodate a decarbonization technology with an SF of 16,000m^2 in its consolidated configuration.

5.4.2. Impact of site-layout constraints on opportunity costs

The SV graph generated, accounting for site-layout constraints at the case study site and the merit order of utilization of such space for the case study plant, is presented in Supplementary Material S.7. An illustrative calculation example for the estimated opportunity cost (DS-I) of occupying available space as lost annual revenue in relation to the value gained from the same space in the reference plant can be found in the Supplementary Material S.7. The estimated lost annual revenue ranges for the deployment scenarios are presented in Table 8. From Table 8, it can be observed that a lower spatial footprint results in a lower loss of annual revenue and associated opportunity costs (see Fig. 14). However, for DS-II (with VF_{nl}), a lower loss in annual revenue is expected due to its fragmented configuration compared to its counterpart configuration with lower SF requirements (~10605m^2). This is due to the placement of decarbonization equipment in Brownfield-II (see Table 3), further away from the core process. Nonetheless, the cost associated with dismantling and removing existing equipment in the Brownfield-II region, which was not accounted for in this work, is expected to increase the estimated lost annual revenue further.

Opportunity cost of decarbonizing the plant: Fig. 14 illustrates the sensitivity of the CO_2 avoidance cost (C_{OC_total}), which includes the baseline avoidance cost estimates (Fig. 7) and the estimated opportunity cost (C_{OC}, as per Eqn. (13)), for varying averaged EU-ETS price over the residual plant lifetime. Here, deployment scenarios with conservative SF estimates (DS-I and DS-III) are compared. In Fig. 14, the curves indicate the net cash flow realized (i.e., the difference between the opportunity cost of occupying space on-site and the avoided cost of EU-ETS permits due to decarbonization measures) in each operational year for the residual lifetime of the plant (~20 years). The net present value of these cash flows accounted for the CO_2 avoided over the residual lifetime, resulting in a CO_2 avoidance cost range for each decarbonization scenario, as shown in Fig. 14. A C_{OC_total} value lower than the baseline avoidance cost estimates (CAC, from Fig. 7) implies that the avoided cost of EU-ETS permits is the dominant factor compared to the opportunity cost, highlighting the benefits of early deployment of decarbonization technology. In contrast, a C_{OC_total} value higher than the baseline avoidance cost implies that the opportunity cost is the dominant cost factor, further accentuated by lower EU-ETS permit prices, highlighting economic risks associated with the early deployment of decarbonization technology that occupies valuable space on-site.

Four conclusions can be drawn from Fig. 14, comparing the site-specific opportunity cost for Post-CCS and Pre-CCS pathways – (i) the difference between the assumed SV functions (VF_l and VF_{nl} typically ranged between 8 and 10 €/tCO_2, irrespective of the decarbonization technology, due to their pre-determined placement at the case study plant. This implies that the assumed linear and non-linear space value functions based on the process design hierarchy have little impact on the final opportunity cost calculations compared to the placement within the case study plant. Nevertheless, the max/min approach to SV functions enables a robust way to estimate a narrow opportunity cost range for different decarbonization technologies at an early stage of assessment; (ii) similarly, the impact of the spatial footprint was found to be marginal, compared to the impact of the location at which the decarbonization equipment is placed within the plant boundaries, as highlighted in Fig. 13. The placement is also further influenced by the installation configuration chosen based on the site layout. Detailed findings from scenarios DS-II and DS-IV can be found in Supplementary Materials S.11; (iii) From the baseline CAC estimates, the net increase or decrease observed in C_{OC_total} was highly dependent on the decarbonization technology and the average anticipated EU-ETS price over the residual lifetime of the plant. For example, the estimated C_{OC_total} for the Post-CCS process (Fig. 14a) was above its baseline avoidance cost (94.3 €/$tCO_{2,avo}$), except for one occasion, representing an unlikely scenario with a high EU-ETS price of 225 €/$tCO_{2,avg}$. In contrast, the Pre-CCS process (Fig. 14b) was estimated to have near equivalent C_{OC_total} as the estimated baseline avoidance cost at a moderate EU-ETS price of 150 €/$tCO_{2,avg}$, which is a plausible scenario in the short term; (iv) In Fig. 14a residual plant lifetime of 20 years was assumed, which implies a lower (<20years) residual lifetime would result in significantly higher C_{OC_total}. For example, the avoidance costs could increase by 25 % to 60 % (from the baseline CAC estimates) to reduce the operational lifetime of the CCS equipment ranging from 20 to 10 years. Overall, comparing the two decarbonization technologies, the estimated variation of C_{OC_total} from the baseline CAC was estimated to be +15 %/−5 % and +19 %/−15 % for the Post-CCS and Pre-CCS processes, respectively. In addition, the estimated C_{OC_total} ranges for the Post-CCS process were approximately 15–28 €/$tCO_{2,avo}$ higher C_{OC_total} than the Pre-CCS pathway.

5.4.3. Local CO_2 interconnection costs

Fig. 15 shows the sensitivity of the cost of local CO_2 interconnection components to the required length and flow rates at a specific site. In Fig. 15, the X-axes and Y-axes show the volumetric flow rate (10ˆ3 Nm^3/h) and the ducting and piping length (m). Z-axes indicate the corresponding CAPEX (M€) for varying flow rates and length. Note that the scales in Fig. 15 differ for each component, and the color bar indicating CAPEX is adjusted to the maximum value estimated in the sensitivity analysis. The estimated CAPEX of each network component in the case study plant is indicated with markers for Post-CCS (Δ) and Pre-CCS process (◊). In general, it can be observed that flue ductwork costs (1–12 M€) more than solvent piping (0–3 M€), followed by the piping for liquefied CO_2 (0–1 M€), confirming the traditional approach to keep the CO_2 capture equipment close to the emissions source to minimize ducting costs.

Comparing the volumetric flow rates of the transported gas/liquid, the liquified CO_2 piping costs, typically at higher pressures, were less impacted by increasing amounts of liquefied CO_2 when compared to the capture solvent or flue gas flow rates. In contrast, the impact of transport distances was profound in all network components, with the largest impact on flue gas ductwork, followed by solvent piping and liquified CO_2 piping. Note that these costs were subject to limitations imposed by the site layout. They could only be estimated with information specific to the layout of a particular process plant and the available space within the plant where capture equipment could be accommodated and installed.

The total CO_2 interconnection costs for the case study plant were estimated to be roughly three times for the Post-CCS process (3.8 M€) than for the Pre-CCS plant (1.17 M€). The breakdown of these costs is presented in Table 9. Even though these cost estimates were relatively minor compared to the baseline estimates from the s-TEA method, in absolute terms, the Post-CCS pathway is expected to incur 3 to 5 times higher contribution in terms of capture (C_{netw_cap}) and avoidance (C_{netw_avo}) costs that the Pre-CCS process. Note that these cost estimates are specific to the case study plant and are expected to vary significantly between sites, for which the local CO_2 network cost estimation tool (Supplementary Material S.4) could be used.

Table 9
Estimated local CO_2 interconnection costs and corresponding contribution (C_{netw}) to the total cost of retrofitability.

CO_2 network components	Unit	Decarbonization pathways	
		Post-CCS	Pre-CCS
Flue gas ductwork	M€	3.10	0.89
Solvent piping	M€	0.42	0
CO_2 piping	M€	0.29	0.28
Total local CO_2 network (C_{netw_total})	M€	3.80	1.17
Specific cost of CO_2 capture (C_{netw_cap})	€/$tCO_{2,cap}$	0.76	0.25
Specific cost CO_2 avoidance (C_{netw_avo})	€/$tCO_{2,avo}$	1.06	0.22

5.4.4. Cost of forced downtime

Fig. 16 shows the influence of the duration of forced downtime or plant stoppage on CO_2 capture and avoidance costs. The values shown represent the cost increase and do not include the baseline CAP and CAC estimates from the s-TEA method.

Fig. 16 shows that the cost of forced downtime (in €/$tCO_{2,avo}$) is a significant cost-escalation factor, which accrues with increased plant shutdown periods. For example, a forced downtime of 1 month could result in an avoidance cost escalation of 23 €/$CO_{2,avo,}$ and 16 €/$tCO_{2,avo}$ for the Post-CCS and Pre-CCS pathways, respectively. Fig. 16 indicates that the Pre-CCS pathway, although with a higher investment cost, constitutes a lower overall risk associated with forced downtime than the Post-CCS pathway, incurring on average 45 % lower forced downtime costs, irrespective of the duration of the plant stoppage. For instance, in the case study plant with major overhauls conducted over three months, the corresponding forced downtime costs, i.e., a delay of 3 months, could result in an additional 69 €/$tCO_{2,avo,}$ and 47 €/$tCO_{2,avo}$ for the Post-CCS and Pre-CCS process from their baseline estimates (Fig. 7). Such significant cost escalation emphasizes the importance of aligning the planned year of commissioning and operation of the CCS plant with the scheduled turnaround year of the case study plant to mitigate the risk of potential cost overruns.

5.4.5. Cost of premature decommissioning (lock-in effect)

Fig. 17 shows the impact of the lock-in effect on the CO_2 avoidance costs (Eq. (17)) for the Post-CCS (blue curves) and Pre-CCS (green curves) processes. The assumed end-of-life of the case study plant (Y_{ey}) corresponds to the Swedish long-term target of net-zero greenhouse gas emissions by the Year 2045 (Government Offices of Sweden, 2017). Note that the extended plant lifetime until 2053 (Y_{ex_ey}) would require reinvestments in the existing assets, and it would also necessitate new investments in decarbonization measures to operate without CO_2 emissions beyond 2045. The black dashed vertical lines indicate the turnaround years that occur every six years. With the most recent one undertaken in 2021, five scheduled turnarounds are expected until 2053.

In Fig. 17, the Year 2025 is the earliest possible CCS deployment year (Y_{dy}) that is able to utilize the entire design lifetime of the DT (20y) until the scheduled decommissioning year 2045, whereas the Year 2033 (Y'_{dy}) exemplifies a CCS deployment year that is synchronized with a turnaround year to avoid cost overruns due to forced downtime (see Section 3.2.4.1). However, such a delay in CCS deployment implies that reinvestments are necessary to extend the host plant's lifetime until 2053

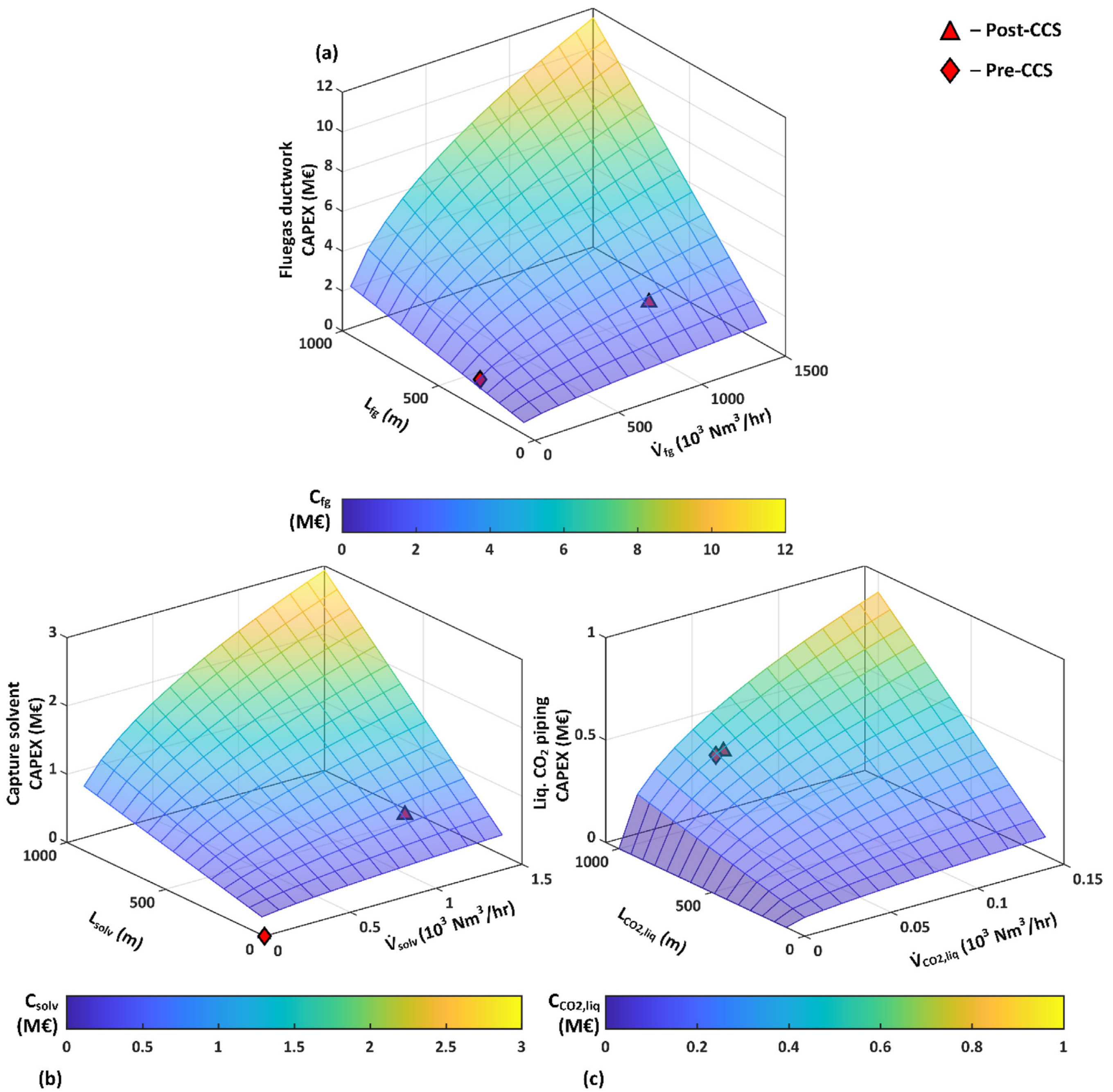

Fig. 15. Influence of site-layout dependent lengths of ducting and piping and plant-specific volumetric flow rates to the total CAPEX of local CO_2 interconnections within plant boundaries. Note that the axes and color bar axes have different scales in each subplot.

to be able to fully utilize the design lifetime of the installed decarbonization technology. The solid blue and solid green cost escalation curves correspond to $Y_{ey,}$ while the dashed blue and dashed green cost escalation curves correspond to the Y_{ex_ey}. The green solid horizontal line represents the zero-cost escalation due to premature decommissioning in the Pre-CCS process, as it provides the possibility to operate as a standalone process plant beyond the lifetime of the case study plant. Nevertheless, in Fig. 17, the cost escalation for the Pre-CCS process (green curves) is visualized to compare with the Post-CCS process, which tends to be locked into the case study plant.

It is evident from Figure 17that the reduced operational lifetime of the installed CCS equipment escalates the cost of avoidance, resulting in $C_{PD\_total,avo}$ as per Eq. (17). For example, a reduction from the design lifetimes of 20 years to 5 years could escalate the avoidance costs from the baseline avoidance costs of 77 €/t$CO_{2,avo}$ (Pre-CCS) and 94 €/t$CO_{2,avo}$ (Post-CCS) to 135 €/t$CO_{2,avo}$ (Pre-CCS) and 134 €/t$CO_{2,avo}$ (Post-CCS), respectively. These cost trends remain the same, with a delayed deployment in the Year 2033 (Y'_{dy}), as no plant reinvestments were considered in the calculations. Overall, the Pre-CCS process tends to have lower avoidance costs than the Post-CCS process due to its higher CO_2 avoidance capability (see Section 5.2.1). In addition, as expected operational years decrease, the gap between the two options converges from a percentage difference of 20 % to 1 % due to the higher upfront investment required for the Pre-CCS process. However, as discussed previously, the Pre-CCS process is expected to be unaffected by delayed installation (green horizontal line) and thereby expected to operate for

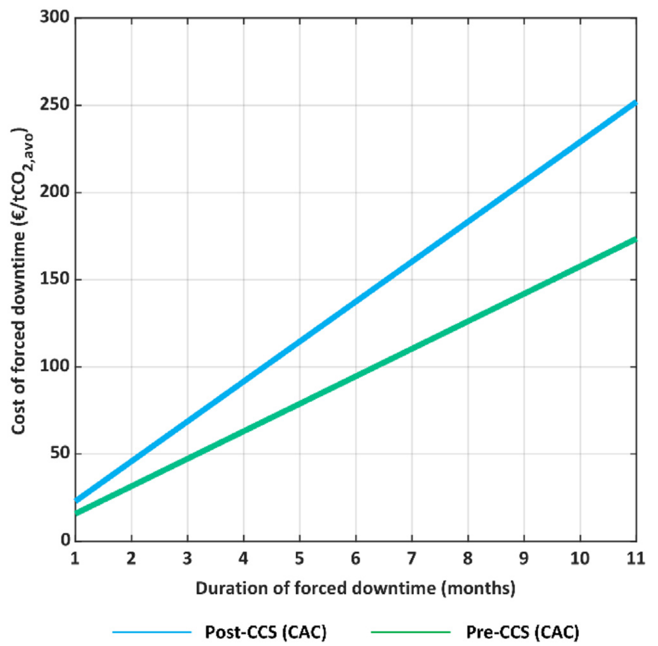

Fig. 16. Sensitivity of forced downtime costs to the plant stoppage/downtime duration. Note that the X-axis ranges from 1 to 11 months, accounting for the scheduled annual maintenance shutdowns lasting one month. Forced downtime costs (C_{FD}) represent the additional site-specific cost incurred due to forced downtime.

its total design lifetime. Therefore, assuming a CCS deployment year of 2033 and the scheduled plant decommissioning year of 2045, the corresponding contribution to the total cost of retrofitability (Section 3.5.5) remained 0 €/tCO_{2,PD_avo} for the Pre-CCS process while the Post-CCS process was estimated to incur an additional 8 €/$tCO_{2,PD\_avo,}$ with a reduced operational lifetime of 12 years (see Fig. 8).

5.4.6. Site-specific indication on cost-optimal decarbonization pathway

The cost of retrofitability (Eq. (19)), accounting for the site-level constraints, and the resulting site-specific cost of CO_2 avoidance were used to obtain an enhanced quantitative comparison between the two decarbonization pathways considered for the case study plant. Considering the deployment scenarios (see Table 8), accounting for all quantified site-specific factors, at an average EU-ETS price of 75 €/tCO_2 over the residual lifetime of the plant, the site-specific cost of CO_2 avoidance, as per Eq. (20), was estimated[20] to range between 144 and 207 €/$tCO_{2,avo}$ (DS-I), 175–192 €/$tCO_{2,avo}$ (DS-II), 104–139 €/$tCO_{2,avo}$ (DS-III), and 108–146 €/$tCO_{2,avo}$ (DS-IV). Notably, the highest avoidance cost estimated for the Pre-CCS process (146 €/tCO_2, DS-IV) was nearly equal to the lowest estimated avoidance cost for the Post-CCS process (144 €/tCO_2, DS-I). In other words, the most cost-effective deployment scenario for the Post-CCS process with a rather conservative estimate[21] was comparable to the most pessimistic deployment scenario[22] for the Pre-CCS process, with a higher bound SF footprint and maximum SV function. Considering the two main cost contributing factors to the cost of retrofitability, i.e., the spatial footprint and the cost of forced downtime, for the given site condition, it was determined that the Pre-CCS process is the lowest cost decarbonization pathway for the case study

[20] The upper and lower bound estimates correspond to the non-linear and linear SV functions used in the opportunity cost calculations.

[21] Its higher-bound spatial footprint estimate (10605 m2) with non-linear SV function.

[22] Its higher-bound spatial footprint estimate (10888 m2) with linear SV function.

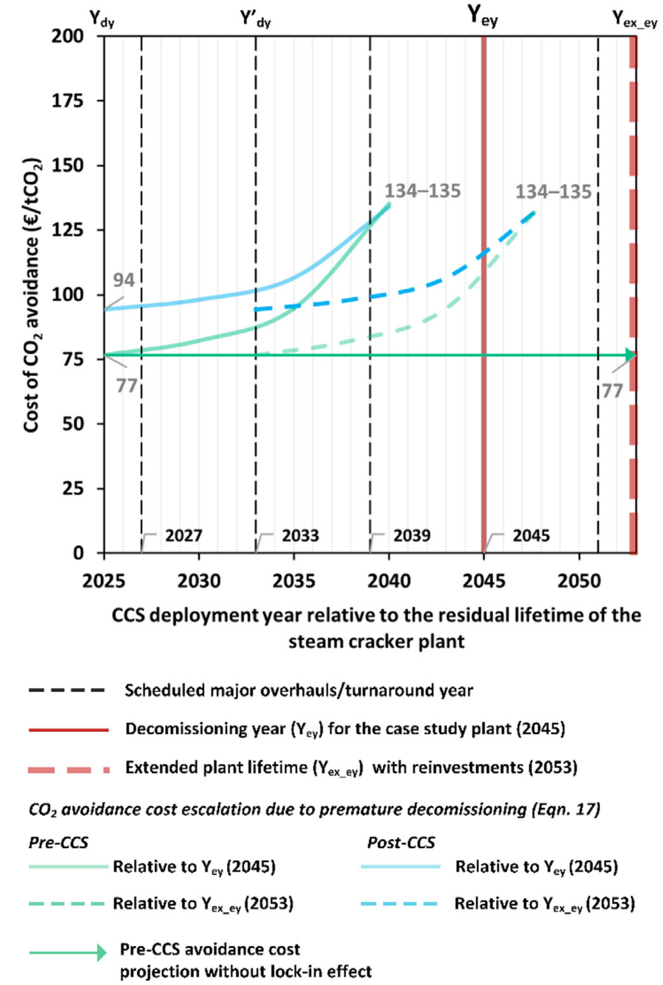

Fig. 17. CO_2 avoidance cost escalation (C_{PD_total}) due to premature decommissioning relative to the residual lifetime of the steam cracker plant. Red solid line – scheduled decommissioning year of 2045 (Y_{ey} ~2045); Red dashed line – extended decommissioning year (Y_{ex_ey}~2053); Black dashed lines – turnaround years that occur every six years. Figure abbreviations: Y_{dy} – CCS deployment year, Y'_{dy} – Synchronized deployment with turnaround year, which enable full utilization of CCS design lifetime until Y_{ex_ey}.

plant, with lower overall risk of cost escalation to its site-specific CO_2 avoidance costs.

5.4.7. Diagnostic diagram

Fig. 18 illustrates the quantitative and qualitative results from the site-specific TEA method applied to the case study steam cracker plant on the diagnostic diagram. In Fig. 18, a higher score for a specific decarbonization pathway implies a higher absolute cost, higher sensitivity, or higher impact on the host plant considering retrofitability aspects (recall Table 4) compared to the alternative decarbonization pathway.

Based on expert elicitation, in general, qualitative factors such as the flexibility to adapt to future feedstock switches, resource availability, alternative use of CO_2 capture equipment, the possibility of reaching 100 % carbon recovery towards CO_2 utilization pathways, cost of retrofitability in terms of CO_2 avoidance, spatial footprint, and lower sensitivity to fuel price tend to favor the Pre-CCS process. In contrast, factors such as system integration complexity, sensitivity to electricity prices, dependence on external energy supply, and external infrastructure favor Post-CCS. The benefits and limitations of each site-specific qualitative factor in the context of retrofitting decarbonization technologies at a steam cracker plant are summarized in Supplementary Material

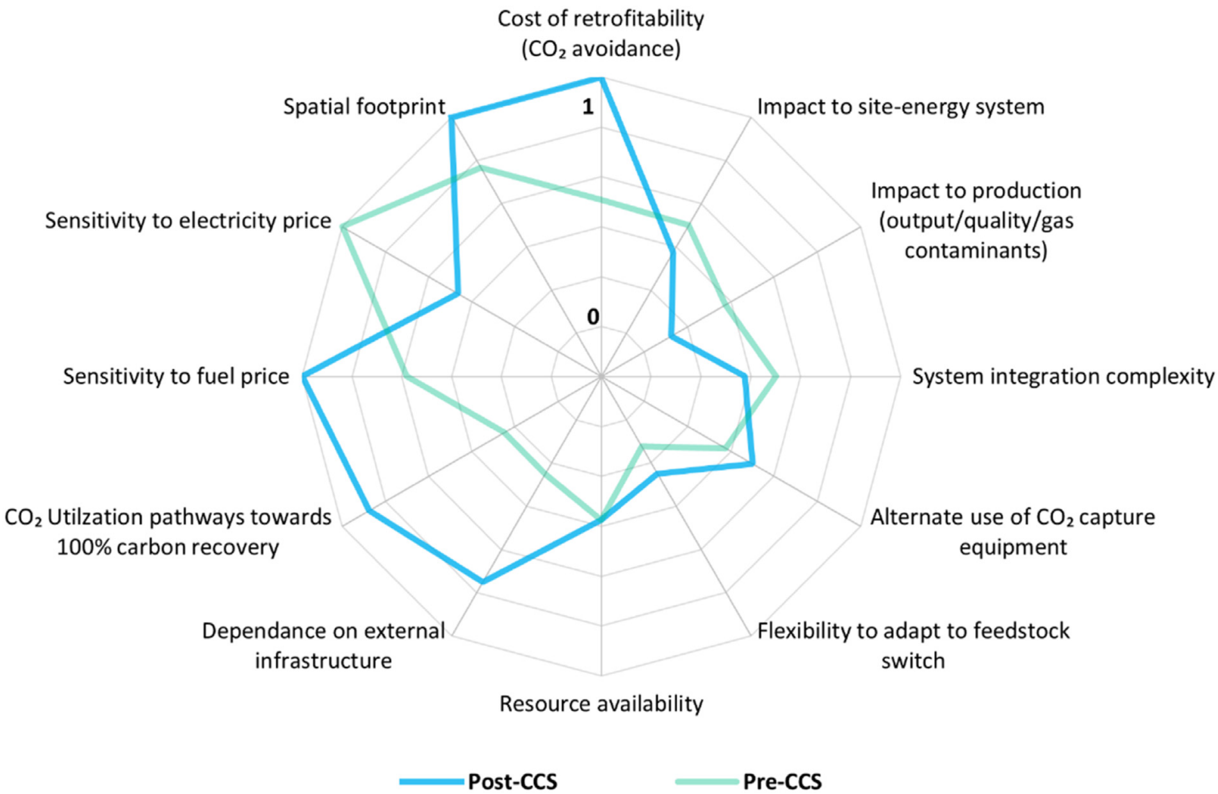

Fig. 18. Diagnostic diagram visualizing quantitative and qualitative results for the case study plant. Note that averaged values of the expert elicitation on qualitative factors are plotted.

S.5.1. The diagnostic diagram for the case study steam cracker plant indicates that the Pre-CCS option, with an average score of 0.47 (lower spread on the diagnostic diagram), is the better decarbonization alternative than the Post-CCS pathway, with an average score of 0.59, that implies higher risks and economic uncertainty.

6. Discussions

The methodological framework applied in this work confirms the significance of considering site-level factors at an early stage when comparing different decarbonization options for carbon-intensive process plants. The quantification methods and estimation tool were generalized to quantify the site and technology-specific cost escalations at an early stage, which, however, require site-specific information to assess the impact with some certainty. In particular, site-specific information such as the existing site-energy system, the site layout, maintenance schedules, placement, and operation lifetimes of existing assets are essential prerequisites for quantifying the impact of opportunity cost, site-layout dependent interconnections, and energy supply options and conducting site-specific TEA. Sensitivity analysis on factors such as forced downtime and premature decommissioning due to the technology lock-in effect demonstrated the technology disparity in expected cost escalations expected from delays during installation in the short term and deployment in the long term relative to the residual lifetime of the host plant. A retrofitability assessment matrix was applied in this work to qualitatively assess key site-specific factors, with elicitation from individuals cognizant of site-level conditions at the case study plant, to confirm whether it further supports or challenges the cost-optimal indication of the decarbonization technology from the site-specific TEA. The following section discusses the practical implications and limitations of investigated site-specific factors, followed by an overall discussion on the usefulness of site-specific TEA.

6.1. Implications of identified site-specific factors and their findings

6.1.1. Forced downtime

The cost of forced downtime was estimated to be the most significant contributing factor to the cost of retrofitability, which could add up to 16–18 €/t$CO_{2,avo,}$ to the baseline avoidance cost estimates, for a minor shutdown period of one month. This cost escalation emphasizes the importance of synchronizing the installation (tie-ins) of decarbonization technology with scheduled annual maintenance shutdown periods (∼1 month) and preferably synchronizing with longer scheduled shutdown periods (∼3 months during turnaround years) to minimize the unforeseen risks associated with the complexity of the integration. The cost of forced downtime is expected to be specific to both the chosen decarbonization technology and the type of process industry and, hence, must be assessed on a case-by-case basis. Expectedly, process industries with shorter shutdown periods, longer recurring periods for turnarounds, and lower operational experience with certain decarbonization technologies are more susceptible to the cost of forced downtime. The impact on production directly translates to an added CAPEX incurred during construction, implying that these supplementary funds must be secured before construction to minimize overall risks. Overall, longer forced downtime periods (>6 months) could be detrimental to retrofit decarbonization measures and would eventually compete with the alternative of dismantling the existing process plant for the construction of a decarbonized or carbon capture-ready process plant, as was demonstrated by Rohlfs and Madlener (2013) for coal power plants.

6.1.2. Spatial footprint of decarbonization technologies and associated opportunity cost

As highlighted by recent works on CCS applications in different process industries (Garðarsdóttir et al., 2019; Hills et al., 2016; Roussanaly et al., 2021), space availability is expected to be one of the key determining factors for decarbonization retrofit measures at existing process plant sites. To this end, this work provides an early-stage spatial footprint estimation tool to determine spatial footprints ahead of basic or detailed engineering design (corresponding to AACE Estimate Class 2 or Class 3) for a specific plant and thereby assess its practical implementation challenges based on site-layout construction, and additionally quantify the opportunity costs of occupying the identified space for decarbonization equipment on-site.

The SF estimation tool relies on publicly available data from FEED reports to generate correlations for spatial footprints dependent on flue gas properties to approximate spatial footprint requirements for other process plants. The estimation tool could be used for process plants with CO_2 concentrations ranging from 4 vol.% to 13.6 vol.% CO_2 and flue gas flow rates ranging from 250 to 710 kg/s. The limitations of the SF estimation tool are discussed in Section 6.2. For the case study plant, the estimated SF for an amine-based capture plant (including compression and liquefaction) was roughly 3 to 4 times higher than the incumbent spatial footprint methods, indicating that incumbent methods are bound to underestimate spatial footprint requirements, which could further contribute to a lack of early-stage insight into practical implementation challenges and associated cost escalation at space-constrained process plants.

This work presented a generalized approach to categorizing process plant layouts based on the proceed-design hierarchy and allocating a value to space available on-site based on the annual average revenue of the plant, which established a link between the space required by different decarbonization alternatives and the cost of emitting CO_2, as the opportunity cost of occupying such space. In particular, this addresses the dilemma of installing the best available technology for decarbonization in the short term, in anticipation of the discontinuation of free allowances (European Commission, 2023; European Parliament, 2023) as opposed to the option to continue operating unabated while being subjected to the EU-ETS price in anticipation of installing emerging decarbonization technology at a later date. The results of this work (see Fig. 8) indicate that the opportunity costs are the second highest contributing costs to the cost of retrofitability, which were highly sensitive to the assumed average EU-ETS price over the residual lifetime of the plant, followed by the space required and equipment placement within the plant.

Future EU-ETS permit prices are expected to be relatively uncertain compared to the technology-specific space requirement and equipment placement, which ultimately depend on the site layout constraints. For instance, occupying large spaces close to core production units of a steam cracker plant is expected to be sub-optimal use of valuable space on-site, as future installation possibilities (of olefins-production technologies, e.g., e-crackers (Borealis Group, 2021) or thermochemical recycling of plastic waste for olefins-production (Cañete Vela et al., 2022; Thunman et al., 2019) would be hindered, as these units should be ideally placed closed to the existing product recover section. In this regard, the Pre-CCS process offers a significant advantage over the Post-CCS process (C_{OC_total}, Table 8) as its process equipment could be placed away from the core-production and product recovery units, with access to the existing fuel gas system, which may require revamping to be able to deliver hydrogen (>>50vol% in the current fuel gas) to the cracker furnaces. In contrast, placement close to the emissions point source is generally preferred to minimize flue gas ducting requirements in the Post-CCS process.

In contrast, results from the sensitivity analysis with variation in averaged CO_2 price, ranging from 0 to 225 €/tCO_2, indicated that the opportunity costs dominate at lower CO_2 price ranges (<150 €/tCO_2), resulting in an avoidance cost higher than the baseline avoidance cost estimates for both Post-CCS and Pre-CCS process. Higher CO_2 prices could potentially offset the estimated opportunity cost partially or completely, depending on the level of equivalent CO_2 avoidance attained with either technology. Results indicated that the opportunity cost of installing the Pre-CCS process was more than offset for a CO_2 price higher than 150 €/tCO_2, as shown in Fig. 14a and b, whereas the Post-CCS process under no price scenario was able to fully offset the opportunity cost. This implied that the eventual site-specific avoidance cost, which includes the opportunity cost, would always be higher for the Post-CCS process than the Pre-CCS process. In addition, the results from the sensitivity analysis on the equivalent CO_2 avoided relative to the current cracker plant emissions confirmed that even in a highly optimistic scenario (assuming 0 gCO_2/kWh emissions intensity for additional electricity and steam consumption), the Post-CCS process is limited to a maximum AC_{eq} of 75 %, which is eight percentage points lower than the Pre-CCS process with similar conditions.

In a broader context, the averaged EU-ETS permits price, discounted with the net-present-value method applied in this work, is comparable to a mutually agreed strike or contract price for CO_2 between industrial actors and authorities as part of the so-called Carbon Contracts for Differences (CCfDs) (Gerres and Linares, 2022; McWilliams and G. Zachmann, 2021). This instrument requires the industrial actor to compensate the authorities when the market EU-ETS permits price exceeds the mutually agreed strike price under the CCfDs, and conversely, the industrial actor gets compensated when the market EU-ETS permits price is below this strike price. Such an instrument ensures price certainty, profitability of decarbonization projects, and competitiveness with other unabated industry actors. In general, a higher strike price incentivizes early deployment of decarbonization measures and alleviates risk for the industry. Considering the results from the opportunity cost sensitivity analysis (Fig. 14), the Pre-CCS process offers significantly lower economic risk compared to the Post-CCS process for the case study plant, albeit requiring significantly higher upfront investment.

6.1.3. Pre-mature decommissioning (lock-in effect)

Results in Fig. 17 highlight the impact on avoidance cost due to the reduced economic lifetime of decarbonization technologies as a result of locking into the host process plant. In general, this cost factor is expected to be insignificant for newly commissioned process plants with a residual lifetime greater than 20–25 years (equal to the design lifetime of decarbonization technologies.) However, the timing of installation of decarbonization equipment is expected to be a major cost escalation factor for legacy industries such as steam cracker plants in the EU. Results indicated that from a design lifetime of 20 years, a reduction in the economic lifetime of newly installed could add up to 0–50 €/t$CO_{2,avo}$[23] to the baseline avoidance cost, depending on the decarbonization technology. As previously highlighted, the installation timing should ideally coincide with the turnaround years to minimize cost escalation due to forced downtime. However, a limited number of turnaround years for the case study plant until its assumed end-of-life implied that there is a trade-off between early installation during a regular year, as opposed to timing the installation with the next turnaround year, albeit with an added risk of a lower economic lifetime of the decarbonization technology. In general, due to the relatively higher integration complexity of the Pre-CCS process than the Post-CCS process, installing during a turnaround year would likely be preferable. Nevertheless, the Pre-CCS process is expected to remain unaffected due to the delayed implementation due to its higher overall CO_2 avoidance possibility, as well as its limited lock-in effect, as it offers an additional possibility of operating as a standalone plant beyond the lifetime of the host plant. Therefore, the Pre-CCS process is expected to outperform the Post-CCS alternative in this aspect.

6.1.4. Site-layout dependent CO_2 interconnection costs

This work provides a simplified network cost estimation tool, based on the network design hierarchy (Berghout et al., 2015) for ductwork and pipelines, to assess these costs at an early stage for other process plants. Estimated cost escalation due to the CO_2 interconnection

[23] Upper bound of 50 €/t$CO_{2,avo}$ corresponds to a reduced economic lifetime of 6 years. Lower bound of 0 €/t$CO_{2,avo}$ indicates full utilization of design lifetime thereby incurring no cost of premature decommissioning.

cost was estimated to be relatively minor (0.2–0.8 €/$tCO_{2,avo}$) compared to the other site-specific factors for the case study plant (see Fig. 15) based on a set of assumptions (see Table 7). The estimated costs depend highly on the site layout and could be a significant cost escalation factor for severely space-constrained process plants, plants with multiple emissions point sources, and those with longer transport distances within plant boundaries. In general, requiring extensive flue gas ductwork would result in significantly higher interconnection costs. For example, these costs could account for up to one-third of the total direct field costs (Martorell et al., 2023). In industrial clusters and process plants with multiple emissions point sources, optimization tools can be applied to determine cost-optimal strategies for CO_2 capture, pooling, and conditioning (Vantaggiato et al., 2024). Nevertheless, to identify a practically feasible interconnection configuration, the optimization tools need to be complemented with methods presented in Section 3.5.1–3.5.2. Costs associated with other interconnection requirements, such as cooling water, steam, condensate, and wastewater lines, could further enhance the site-specific interconnection costs.

6.1.5. Overall comparison of decarbonization options

Results (Fig. 9) indicate that the Post-CCS is limited to a maximum equivalent CO_2 avoidance of 85 % while the Pre-CCS process attains a maximum equivalent CO_2 avoidance of 96 %. An increase in equivalent CO_2 avoidance in the Post-CCS process could be realized with higher capture rates (>90 %) to minimize vented CO_2 and the introduction of biogenic feedstock into the steam cracker plant. In contrast, the Pre-CCS process, if complemented with the introduction of biogenic feedstock, is expected to enable net-negative CO_2 emissions on-site, depending on the extent of feedstock substitution. Considering the limited number of years until the targeted net-zero emissions year (2045), the timing of CCS installation is relatively more critical for the Post-CCS process than the Pre-CCS process due to their inherently different lock-in effects. In the context of steam cracker plants in the EU with limited residual operational lifetimes, synchronization of the design lifetime (20y) of the Post-CCS process with the residual plant lifetime would be required to avoid premature decommissioning. For the case study plant, this implies an installation of the Post-CCS process as early as 2025 and, at the latest, 2033. Despite the CO_2 reduction obtained in the short term, the Post-CCS process is, therefore, not expected to play an important role in steam cracker plants as it would not meet the net-zero CO_2 emissions target. In contrast, the Pre-CCS process is expected to provide a compounded benefit with the introduction of biogenic feedstock to achieve net-negative CO_2 emissions with process equipment that could be operated well beyond the residual lifetime of the existing steam cracker plant. Nevertheless, changes to the existing steam supply systems for low-carbon electricity generation capacity on-site could be considered to hedge against the limited availability of renewable electricity and high electricity prices.

6.2. The usefulness of early-stage site-specific TEA and its limitations

The site-level implications are bound to impact technologies differently, as demonstrated in this work, resulting in different total costs of retrofitability and, ultimately, the choice of decarbonization technology. The strength of site-specific TEA lies in its ability to obtain an early-stage indication of the cost-optimal decarbonization option, with the quantified site-specific factors, which is complemented by qualitative evaluation of additional site-level factors that are independently reviewed to obtain a concrete and holistic indication on the optimal choice of decarbonization technology. In particular, it helps to highlight the differences between different technological options on a higher level of detail often not considered in standardized TEA analysis and thereby assists decision-making towards implementing decarbonization measures.

It is important to note that results obtained from the site-specific TEA method are expected to be highly case-specific, limiting its comparability with other results for a similar process plant within the same industry category. However, the comparability of results between similar process plants was not the objective of the developed method. Instead, the objective was to modify the incumbent standardized TEA methods to make such pertinent data, extracted from literature, site-specific, aiding decision-making at an early stage. Nonetheless, extracting site similarities and differences within the same industry category would further aid the developed method in making informed site-specific assumptions applicable to most process plants within the same industry category. Other limitations include the wide range of spatial footprint estimates from the SF estimation tool, primarily due to the limited detailed FEED data publicly available to date. Therefore, this work motivates the need for transparent data sharing of the spatial footprint of different decarbonization technologies from technology providers and meticulous curation of such data to aid industrial actors in assessing implementation challenges at their sites at an early stage.

Furthermore, the ductwork and piping length requirements between different process equipment units are subject to the final engineering design of the decarbonization technology, thus requiring a set of assumptions at an early stage. In addition, the cost of on-site CO_2 storage, cost of CO_2 transportation outside plant boundaries, dismantling and rearrangement of existing assets, revamping of fuel gas system, additional equipment for handling gas contaminants (e.g., possible increased NO_X emissions from hydrogen firing (Cellek and Pınarbaşı, 2018), and other interconnection costs were not considered. Thus, the capture and avoidance cost can be slightly underestimated for the Pre-CCS process. Nonetheless, as demonstrated by the results and sensitivity analyses (see Fig. 8–Fig. 17), the difference between the estimated CO_2 avoidance cost ranges for Post-CCS and Pre-CCS alternatives is quite significant. More specifically, the significantly higher CO_2 avoidance achieved for the Pre-CCS process compared to Post-CCS, relative to the unabated steam cracker plant, implies that the inclusion of the aforementioned aspects to the avoidance cost estimation would only marginally diminish the cost differences between the two decarbonization technologies. Therefore, the comparative results and analyses that confirm the Pre-CCS process as the cost-optimal decarbonization solution are expected to remain unaffected. The qualitative retrofitability assessment from experts from the case study plant further supports this indication.

Other limitations of this work include the comparability with other possible decarbonization solutions that are not considered. For example, future process changes, such as introducing biogenic feedstock at the steam cracker plant, could motivate a partial capture Post-CCS plant, driven by excess heat on-site, achieving comparable levels of CO_2 avoidance on-site as the Pre-CCS process. In addition, the effect of economies of scale is more pronounced for the Pre-CCS process than the Post-CCS process, which implies that at smaller scales, the equipment costs for the Pre-CCS process could increase significantly. Therefore, the Post-CCS process could become increasingly cost-competitive compared to the Pre-CCS process in such scenarios involving biogenic CO_2, which would, however, need to remain unaffected by the lock-in effect (Section 2.5). Finally, gathering site-level data was deemed the primary limiting factor for conducting a site-specific TEA to compare different decarbonization technologies for a specific plant. However, the framework methodology developed in this study offers insights on utilizing open-source tools, such as Google Maps, for a generalized site layout categorization, which could be complemented with the cost estimation tools provided in this work to reduce dependence on sensitive plant information for future site-specific TEA studies.

Future work could utilize the framework methodology introduced in this work to confirm whether cost-optimal indication from the s-TEA would still hold when site-specific factors are considered for other process industries. For instance, the extensive technical and economic evaluation of the cement industry under the CEMCAP project (Garðarsdóttir et al., 2019) could be complemented with a site-specific TEA method, incorporating technology-specific attributes (Hills et al., 2016) to obtain an enhanced indication of the optimal choice of decarbonization technology for a specific cement plant. The spatial footprint estimation tool provided in this work includes spatial footprint estimates from the FEED report that were publicly available at the time of writing. We recommend incorporating new spatial footprint estimates over time to improve the accuracy of the estimated range for the spatial footprint of the Post-CCS technology. The tool could also be adapted to incorporate future technological advancements that may result in lower spatial requirements. Furthermore, the technology-specific retrofitability costs and spatial footprint estimation could be incorporated into cost optimization models that determine the optimal technology mix for decarbonization. Finally, the impact of these costs could be adopted into energy system studies that evaluate national-level marginal abatement cost curves and the effect of cascading cost of decarbonization on the final consumers, that so far have relied on results from the s-TEA method on different decarbonization technologies.

7. Conclusions

This work introduced the concept of site-specific techno-economic analysis for carbon capture and storage (CCS) in the carbon-intensive process industry, incorporating site-specific factors that are expected to significantly affect the cost of CO_2 capture and avoidance. A methodological framework was introduced that utilizes process modeling and integration tools and combines early-stage standardized techno-economic (s-TEA) methods with site-specific factors to enhance the comparative assessment of decarbonization technologies. Novel cost estimation tools/methods were introduced for site-specific factors, such as the opportunity cost associated with occupancy of space available on existing sites, local CO_2 interconnections, and costs incurred due to forced downtime and premature decommissioning of newly installed equipment due to locking into the end-of-life of the host plant, together referred to as the cost of retrofitability. The framework was demonstrated with a case study on a steam cracker plant for which two technologically mature decarbonization options were compared: (i) post-combustion CCS with an amine-based CO_2 capture plant and (ii) pre-combustion CCS, deploying steam methane reformers to produce hydrogen as the primary fuel for the cracker furnaces. The following conclusions were drawn from the case study results:

- Accounting for site-specific factors and the site-level conditions, the site-specific cost of avoidance is estimated to be 137 €/t$CO_{2,avo,}$ and 90 €/t$CO_{2,avo}$ for the Post-CCS and Pre-CCS processes, respectively, which is roughly 46 % and 36 % higher than the baseline estimates from the s-TEA method. The lower CO_2 avoidance cost for Pre-CCS is primarily due to electricity consumption with relatively lower emissions intensity, which, through heat recovery, additionally offset significant amounts of CO_2 emissions generated on-site associated with steam generation. Therefore, the cost of retrofitability, or cost escalation due to site-specific factors, in terms of CO_2 avoidance, was roughly 80 % higher for the Post-CCS process (43 €/tCO_2) than the Pre-CCS process (24 €/tCO_2).
- The site-specific capture cost was estimated to be approximately 49 % and 33 % higher than the levels indicated by s-TEA methods, corresponding to a CO_2 capture cost of 101 €/t$CO_{2,cap}$ and 114 €/t$CO_{2,cap}$ for Post-CCS and Pre-CCS processes, respectively. The CO_2 capture costs for the Pre-CCS process tend to be higher due to the higher investment cost to reduce an equivalent amount of CO_2 from the steam crackers as the Post-CCS process. However, the CO_2 capture cost is not a suitable metric for such comparisons due to the inherently different CO_2 avoidance capabilities of the two decarbonization technologies.
- The impact on current or potential production has the largest influence on the total cost of retrofitability. Significant cost escalation could be avoided by synchronizing CCS deployment with scheduled maintenance shutdowns during turnaround years to minimize the possibility of unforeseen forced downtime. For example, a forced downtime lasting 3–6 months resulted in an avoidance cost escalation by 31–79 % from the aforementioned site-specific CO_2 avoidance for the two decarbonization alternatives.
- The opportunity cost associated with utilizing the available space onsite has the second largest impact on the cost of retrofitability. The opportunity cost factor is highly sensitive to the placement of decarbonization equipment at the plant site, the spatial footprint of the decarbonization technology and corresponding installation configuration (i.e., consolidated or fragmented), and the projected cost of emitting CO_2 as an alternative to early deployment of decarbonization measures and technologies.
- The final investment decision on CCS deployment must be made considering the residual lifetime of the steam cracker plants, including future process changes, e.g., feedstock switch that would influence the operational characteristics of the plant and may render installed decarbonization technologies redundant.
- The Post-CCS option is not expected to play a significant role in the decarbonization of steam cracker plants as its CO_2 avoidance performance is insufficient to meet the net-zero CO_2 emissions target. The Pre-CCS option provides significant CO_2 avoidance possibility, which could be enhanced to net-negative CO_2 emission with the introduction of biogenic feedstock and, therefore, entails minimal economic risk with its implementation. Changes to steam supply systems (e.g., installation of low-carbon electricity production capacity onsite) could be considered to provide operational flexibility during periods of high electricity prices.

These results demonstrate how the identification of the cost-optimal decarbonization solution can be enhanced with the site-specific-TEA method incorporating site-level factors of a carbon-intensive process plant. The developed quantification methods and the retrofitability assessment matrix generate new insights at an early stage of comparative assessment, enabling informed decision-making toward decarbonized plant operation. The developed methodological framework, along with the tools designed for spatial footprint and interconnections cost estimations, is generalized and can therefore serve as a basis for evaluating a wide array of decarbonization options in the context of other large-scale process plants, such as pulp mills, cement plants, and oil refineries.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

V.R. Reddy Marthala reports a relationship with BorealisPolyolefine GmbH that includes: employment. Lars Pettersson reports a relationship with Borealis AB that includes: employment. The perspectives/interpretations/conclusions expressed by the co-authors in this scientific article are the personal views of V.R. Reddy Marthala and Lars Pettersson and do not necessarily represent the opinions or positions of the affiliated institution, BorealisPolyolefine GmbH, and Borealis AB.

CRediT authorship contribution statement

Tharun Roshan Kumar: Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Johanna Beiron:**

Writing – review & editing, Methodology. **V.R. Reddy Marthala:** Writing – review & editing, Conceptualization. **Lars Pettersson:** Writing – review & editing, Conceptualization. **Simon Harvey:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Henrik Thunman:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Acknowledgments

The authors thank Tobias Lehle and Marcus Thim (formerly Chalmers University of Technology) for the process modeling of the pre-combustion decarbonization pathway and Qiyu Liu (Chalmers University of Technology) for their assistance with area estimates using *ArcGIS*. We would like to thank Lars Pettersson (Borealis AB) and V.R. Reddy Marthala (BorealisPolyolefine GmbH) for valuable discussion on CO_2 capture possibilities at the steam cracker plant and their inputs on site-specific factors and the retrofitability assessment. We would also like to thank Maximilian Biermann (formerly Chalmers University of Technology) for their valuable input on cost estimation methods and Isabel Cañete Vela (Borealis AB) for their contributions to the retrofitability assessment.

This work was carried out within the framework of the project - Transformative change towards net negative emissions in Swedish refinery and petrochemical industries (FUTNERC), which is a collaboration between Chalmers University of Technology, Borealis AG, and Preem AB, with funding provided by the Swedish Energy Agency (Project 49831-1), Borealis AG and Preem AB.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ccst.2024.100338.

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