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Partial CO_2 capture in process industry – a review of aspects to consider for a cost-effective and timely CCS implementation

Maximilian Biermann*[a], Fredrik Normann [a], Filip Johnsson [a]

[a] *Chalmers University of Technology, Division of Energy Technology, 412 96, Göteborg, Sweden*

Abstract

Carbon capture and storage (CCS) activities need to be ramped up significantly to address the climate crises. This paper reviews relevant techno-economic and policy-related aspects for a cost-effective, near-term implementation of CCS via partial CO_2 capture in the process industry which have been explored in a doctoral thesis from a site-level perspective. These aspects include: 1) the energy- and cost-effective design of solvent-based processes for partial capture, entailing cost savings of up to 10% for CO_2-rich gases (>17 vol.%$_{wet}$); 2) the efficient use of available heat on-site to power partial which can confer cost savings along the entire CCS chain of up to ~25%; 3) the incorporation of site realities, such as temporal variations in heat availability, into techno-economic assessments; 4) the adaption of policies that address the allocation of carbon emissions reductions to low-carbon products, so that investments in mitigation technologies are incentivized with respect to the ambition level; and 5), the recognition of the rather narrow window of opportunity for partial capture with regard to the climate targets of the Paris Agreement and to the lifetime of the existing infrastructure, alternative production and (co-)mitigation technologies, as well as the regional energy and CO_2 transport and storage systems.

Keywords: Partial CO_2 capture; process industry; reinvestment cycles; heat integration; variations management; process design; carbon allocation

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1. Introduction

The current global carbon capture and storage (CCS) capacity is ~40 Mt per annum of CO_2 (Mtpa)[1], whereas the estimated required capacity by Year 2050 congruent with the 2°C goal is ~5,600 Mtpa CO_2, of which ~2000 Mtpa CO_2 are ascribed to process industry (steel, cement, petrochemicals), according to a recent IEA report [2]. Thus, a fast ramp-up of CCS implementation is needed. The economics rather than technology limitations will continue to predominantly govern the investment decision on CCS, if not made a mandatory environmental technology. Thus, there is a need for increased policy measures to, *inter alia,* guarantee a carbon price sufficient to trigger investments. Furthermore, bringing down cost of CCS is important to contribute to closing the gap to current levels of carbon prices, reduce the need for public financing, reduce the economic risk of new business models based on CCS, and thus, overall to facilitate a timely and broad adoption of CCS in process industry. One important vehicle for a fast, near-term

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* Corresponding author: Maximilian Biermann. Tel.: +46 31 772 5253, *E-mail address:* max.biermann@chalmers.se

adoption through cost reduction is partial CO_2 capture, which aims to capture only the cost-effective fraction of the CO_2 emissions [3]. Thereby, the absolute amount of energy and cost for capture is reduced, thus, lowering the dependency on the surrounding energy system and the initial investment risk, as compared to full capture [4], [5]. If these reductions in cost and energy demand make an earlier implementation possible, not only would the CCS infrastructure be built sooner, and the accumulative emissions be reduced, but also the achievement of near-term emission targets (e.g. 55% emission reduction in the EU in Year 2030 compared to 1990) could be facilitated.

This paper is a synopsis of the doctoral thesis by Max Biermann [6] and highlights relevant technical, economic, and policy-related aspects that may facilitate a near-term implementation of carbon capture in process industry. Specifically, the paper elaborates on:

i. Cost-effective design of amine absorption cycles for partial capture of CO_2 from industrial sites.
ii. The relationship between cost, energy consumption, and capture rates in process industry at the example of a refinery case study.
iii. The role of flexibility in carbon allocation of mitigated CO_2 emissions to industrial products.
iv. The impact of heat supply for CO_2 capture in process industry on capture cost and the full-chain CCS cost.
v. An overall perspective on partial capture in synergy with and in the transition to other mitigation options or full capture overtime for relevant industrial sectors.

In addition, the paper highlights the contributions the thesis made to the method development by 1) extending the application of process models to include design pathways for partial CO_2 capture, and 2) by incorporating site-related realities (such as temporal variations in heat supply) into techno-economic assessments (TEA).

The outline of the paper is as follows: Section 2 describes partial capture as concept and the contributions made to the method development; Section 3 summarizes key findings; Section 4 discusses the application for partial capture in selected industries in form of narratives. Section 5 concludes the paper.

2. The concept of partial capture and the contribution to method development

Partial capture of carbon aims, for specific market or site conditions, to capture a designated, economically motivated share of the CO_2 available on-site. Partial capture differs from full capture in that the lower capture rate confers additional technical degrees of freedom that can be used in the application of a solvent-based process. These can include different pathways for column design and different degrees of integration at the site (choice of heat and CO_2 source), and allow the process to be designed for market conditions that will vary over time and that value flexibility. Partial capture sites have the potential to achieve full decarbonization together with co-mitigation measures, and to evolve towards full capture over time. Thus, partial capture may represent a low-risk starting point towards the final destination in the "roadmap" for industrial decarbonization.

A proper overview of the applied methods is given in the doctoral thesis [6]. Here, only the contributions made to the method development (see Introduction) are given. Concerning the inclusion of partial capture process into numeric models, our work [3] has extended previous literature on partial capture [7]–[10] by formally describing two pathways for partial capture design derived from a full capture design (≥90% capture): 1) the *split stream path* (SSP), in which the capture rate is reduced by bypassing parts of the CO_2-rich gas flow, such that a slipstream is treated at a high separation rate of CO_2 in a downscaled absorber (i.e. ~90%); or 2) the *separation rate path* or *off-design path* (SRP/ODP), whereby the entire gas flow is treated but a smaller fraction of the CO_2 in the gas flow is separated (i.e., <<90%). Our recent publication [11] introduces the concept of a full-capture ready design, based on the SRP/ODP which incorporates the possibility to eventually extend the initial partial capture rate to full capture.

Regarding the incorporation of site-related realities into TEAs, the work described here and in [5], extends previous studies on heat supply, which often assumed combined heat and power (CHP) plants as heat supply option (which strongly couples the economics to the value of exported electricity) [12], [13], and which often have assessed heat recovery based on annually averaged heat load values (see, e.g., [4], [14], [15]) and as single-measure alternative to CHP plants [16], [17]. The concept of site-level abatement cost curves introduced in [5] allows: 1) the identification of a mix of heat sources as a function of the steam demand (CO_2 captured); 2) a detailed assessment of the heat recovery potential, e.g., via bottom-up assessments of heat collection networks similar to those reported previously [14], [18], but also considering temporal variations in residual heat; 3) the inclusion of the existing capacity of the site energy system to generate additional steam; and 4) an incorporation of the indirect emissions associated with different energy carriers and, thus, the regional energy context. Therefore, instead of assuming (a single or multiple pre-ranked) heat source(s) based on an annually averaged load, a mix of heat sources is considered that is optimized (cost or energy minimization) and that accounts for the temporal variations present. The ulterior motive is to enhance the representativeness of early TEAs of (partial) CO_2 capture at industrial sites.

3. Main findings

3.1. Partial mitigation raises issue of flexibility in carbon allocation

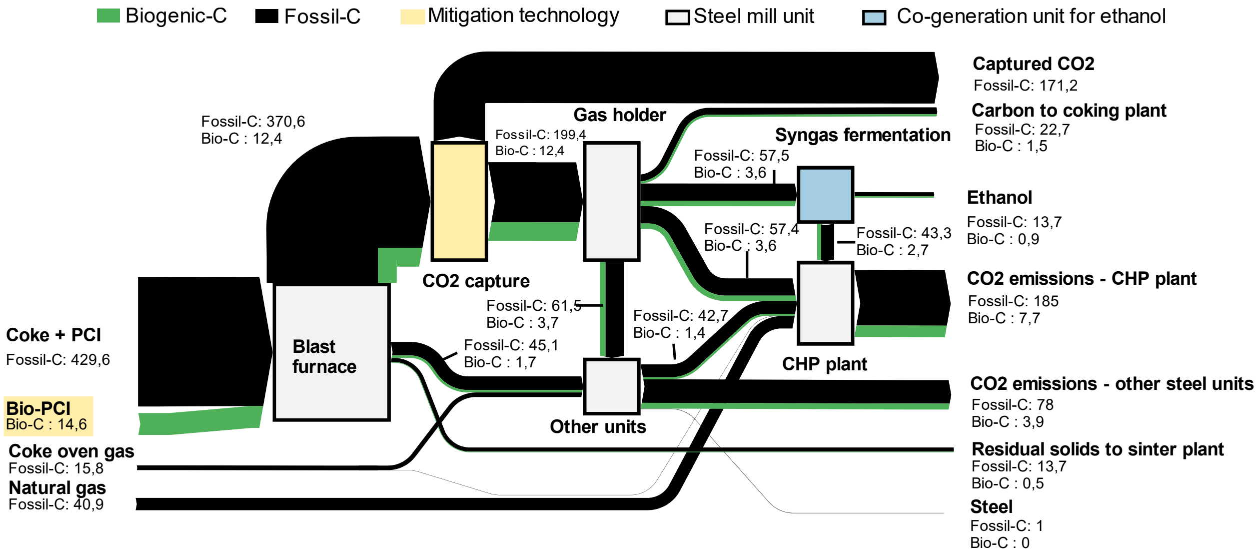
Full mitigation entails zero carbon products. Partial mitigation infers the question whether all products should have the same reduction in emissions intensity or if flexibility in the allocation of emissions savings should be granted.

Fig. 1 demonstrates the impact of the allocation scheme on the assigned biogenic content of the product. It illustrates the example of a steel mill that mitigates emissions by applying CCS (capture from the blast furnace gas) and injecting biochar into the blast furnace (BF) while co-generating ethanol from the same BF gas, as described in [19]. The *allocation by carbon mass* in Fig. 1a mimics the physical realities by assigning each carbon-containing effluent stream of the BF the same share of biogenic carbon, corresponding to the ratio of the biogenic to fossil feedstocks entering the BF. Since most of the effluent streams relate to steel production units, the majority of the biogenic carbon is allocated to the steel product. As explained in [19], this allocation of biogenic carbon and the allocation of avoided emissions via CCS to ethanol (also on mass basis) are not sufficient to allow the ethanol to qualify as bioethanol (criterion: 65% reduction, as compared to 94 gCO_{2eq}/MJ for petrol). A *free-choice attribution* of biogenic carbon to ethanol in Fig. 1b and an attribution of avoided emissions via CCS would, however, enable qualification as bioethanol. Other parameters that influence the carbon intensity of co-generated ethanol are the electricity grid intensity, heat integration, and the extent of biochar injection and CCS.

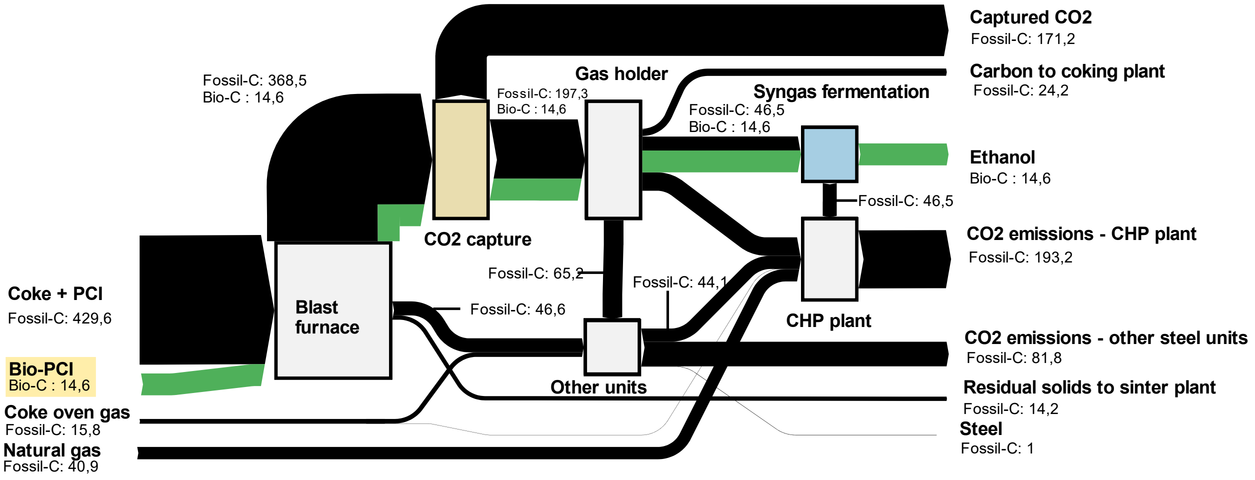
This example highlights the impacts of carbon allocation schemes and poses the question as to the level of flexibility that manufacturers should have in allocating emissions savings linked to verifiable and quantifiable mitigation actions. Table 1 lists motivation as well as risks linked to an increased flexibility in carbon allocation. Ultimately, the regulatory body is left with a political choice when deciding which allocation schemes are valid (since the emissions reduction is independent of allocation). If granted, freedom with regards to the choice of allocation may help to create additional value, and thereby, incentivize mitigation. To mitigate the risks, policy measures could reward ambitious mitigation measures, e.g., by remitting a collected climate surcharge depending on the mitigation degree and by mandating labeling that makes a clear distinction between low-carbon and zero-carbon ('green') products.

Table 1: Motivations and risks linked to an increased flexibility in carbon allocation

Motivations	**Risks**
Emissions savings are independent of the choice of carbon allocation (provided that emissions savings are not counted double)	Some products sold will have an assigned biogenic content that is greater (and some products correspondingly will have one that is lower) than the actual physical biogenic content (if measured)
Emissions savings can be assigned to high-value products that raise revenue and, thus, increase return on an investment made in a mitigation technology.	Flexible attribution and revenues from low-carbon products imply settling for low-levels of mitigation (e.g., partial capture) while maintaining unabated fossil fuel consumption, as opposed to incentivizing immediate, full mitigation
Physical representation allocates most emissions savings to the largest product volumes. For manufacturers of base materials (e.g. steel), the co-generation of high-value, low-carbon products (fuels, chemicals) in relatively small volumes may be disincentivized	Ambiguity and non-transparency with respect to product labeling for the consumer may arise if 'green' products (suggesting the avoidance of fossil feedstocks/energy in production) and low-carbon products are labeled as equal, which might be perceived as greenwashing.



a) Allocation by carbon mass



b) Attribution (free-choice) to ethanol

Fig. 1 Flow of biogenic carbon (green arrows) through a steel mill that has ethanol production and CCS. The allocation between streams is determined through allocation according to the carbon mass (a) and free-choice attribution to ethanol (b). The green arrows are enhanced for visualization purposes (5:1) relative to the black arrows. The values given are kg of carbon per tonne of hot-rolled coil of steel. Note that biogenic carbon is not captured due to the assumption of “fossil carbon first”. Adapted from [19].

3.2. Energy and cost savings through process design for partial capture

Fig. 2 shows that amine absorption cycles can be designed for CO_2 separation rates in the absorber <<90% (e.g., 50%-70%), so to allow for a more energy-efficient operation, i.e., a lower specific reboiler demand (SRD) and cooling demand, which may lower the specific capture cost per tCO_2 by up to 10% as compared to full capture (≥90%). In Fig. 2, the design with lower separation rates (SRP/ODP) is shown in blue, while the alternative SSP design (downscaled full capture design) and the full capture reference are shown as red-dashed line and black square, respectively. Such levels in cost savings were reached for gases with high CO_2 concentration of ~>17 wt.% (e.g., cement kiln, steel mill off-gases, lime kiln, steam methane reformer flue gas).

The underlying mechanism reducing the SRD is coupled to a lower absorber temperature and a lower liquid-to-gas ratio achieved at lower separation rates, which leads to a higher loading of the solvent leaving the absorber, ultimately causing a lower SRD in the stripper. The order of magnitude of energy savings of 7-10% was verified through pilot scale tests of CO_2 capture from steam methane reformer flue gases using MEA [11]. Furthermore, the savings are fundamentally determined by the geometry of the packed column, i.e., the designed packing height and approach to flooding. For generously designed packings (large packing volum), the energy savings of the SRP/ODP design compared to full capture diminishes at lower separation rates [11].

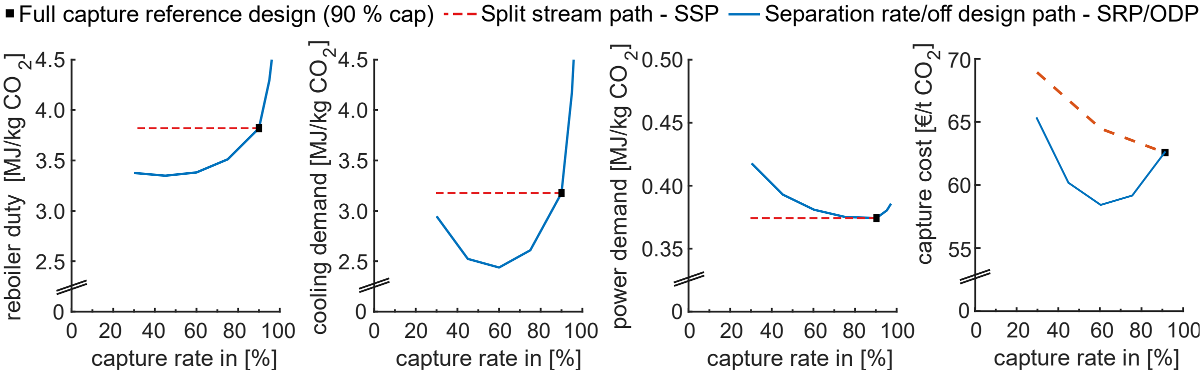


Fig. 2: Comparison of design pathways for partial capture showing the specific reboiler duty, cooling demand, power demand, and specific capture cost (OPEX + CAPEX) for the split-stream path (SSP) and the separation-rate/off-design pathway (SRP/ODP), as compared to a 90% full capture design. The CO_2 concentration in the absorber feed is 20 $\text{vol.\%}_{wet}$. Note that the ordinates do not start from zero. Adapted from [3].

3.3. Management of temporal variations – representation in cost estimates and potential use case

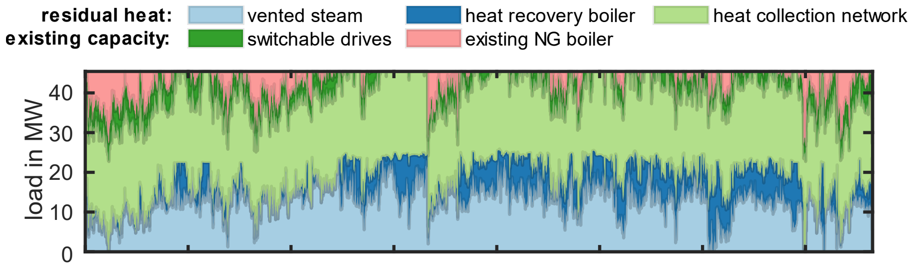
Typically, the production of base materials occurs at a rather constant load throughout the year, with regular maintenance periods (annual, biennial, or longer) during which production is shut down. Concerning the amount of residual heat that can be made available for CCS, two fundamental load characteristics can be distinguished: 1) a rather constant load in recovered residual heat following the load of the industrial process, and 2), an induced seasonality to the availability of residual heat due to varying production levels or energy exports (e.g., district heating). The management of underlying temporal variations in both these cases is presented in the following.

Regarding characteristic 1 (constant load in available heat), Fig. 3a shows that if an on-site industrial energy system (IES) is used to manage temporal variations in residual heat sources (vented steam, heat recovery boiler, heat collection network), a reserve heat source is required, for example existing gas boilers that have sufficient capacity, to guarantee a certain heat supply (here: assumed constant annual load). Fig. 3b shows that the variations could instead be passed onto the capture plant, thus, implying a varying reboiler load. A properly design capture plant can cope with such variations [20]. Fig. 3c depicts the load in residual heat if the real temporal variations are omitted in the analysis. Table 2 summarizes these three cases. It is evident that: 1) managing the variations in the IES so as to achieve a constant load with additional fuel entails a considerable cost and increased emissions; 2) a proper characterization of the temporal variations in heat sources from IES units is essential for obtaining a representative cost for heat supply, and thus capture cost - omitting variations underestimates the capture cost by 12% in this example; and 3) the management of variations in the capture plant versus in the IES may lead to a similar capture cost (~+4 €/tCO_2 compared to a constant load without variations).

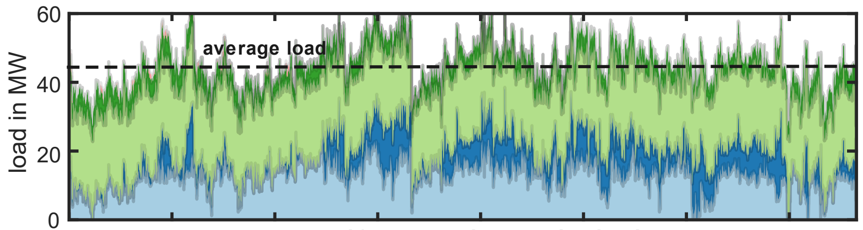
Regarding characteristic 2 (seasonally varying load in available heat): in order to cope with seasonal variations the size of the capture plant (SRP/ODP design) can be adapted to match the peak heat load (in summer in the district heating context) which will lead to a lower utilization of the plant (higher CAPEX per captured tCO_2) during the periods of lower heat load, assuming that the plant follows the load of available heat. Fig. 4 shows the cost of such seasonal operation in comparison to the alternative, i.e., to a plant that is sized (SSP) to avoid the same amount of CO_2 and that operates at a constant load by importing additional energy during periods of low residual heat (increased OPEX). It is evident that the cost of seasonal operation is heavily dependent upon the degree of utilization and the scale. For utilization >~50% and for scales >~400 ktCO_2 per annum, the cost increase is <10 €/tCO_2. Seasonal operation of CCS is a way to retain levels of district heating supply from industrial sites or waste-to-energy (WtE) plants whilst applying CCS. However, in the context of decarbonizing industry, residual heat could be put to better use for CCS, depending on how a reduced district heating supply could be compensated for in the local/regional energy system's context. From the cost perspective, the revenue loss from a reduced district heating supply would be substantial, and could lead to a capture cost similar to that for retaining the district heating supply loads (see [21]).

It should be noted that ~25%–38% of the heat dispatched to the reboiler at 120°–130°C can be directly recovered and utilized for district heating (for details, see the paper by Eliasson et al. [22] and the thesis work of Abrami [23]). Even levels in the range of 89%–126% of the district heating supply can be retained by vigorous heat integration or the use of advanced hybrid heat pumps at the expense of electricity generation, as illustrated for WtE-CHP plants by Hammar [24] and Abrami [23], respectively. Note that this type of heat recovery was not included into Fig. 4, and also that the downstream impact of a variable capture plant load was not assessed here.

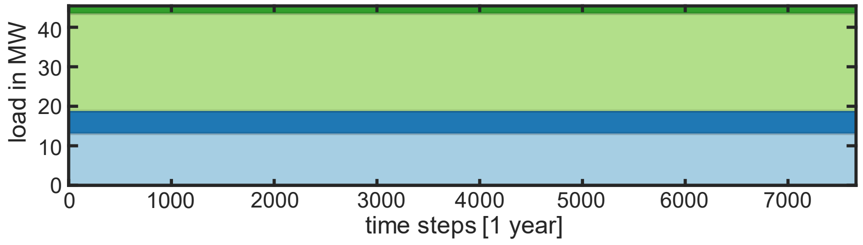
To conclude, the incorporation of temporal variations in the assessment of heat supply for CCS in process industries has a considerable cost impact, and the capabilities of the capture unit and of the site-specific IES in managing variations in heat supply need to be evaluated in terms of their technical and economic feasibility levels.



a) IES consant load



b) capture plant varying load

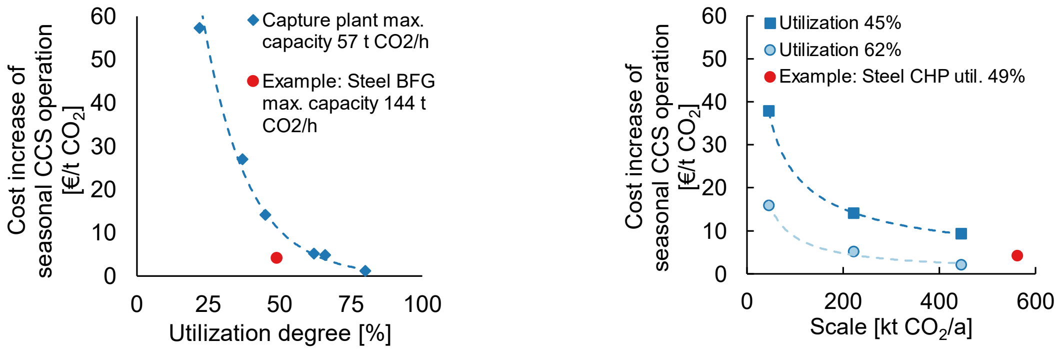


c) variations omitted

Fig. 3: Load distributions of the heat sources that power the capture of CO_2 from the flue gas of a refinery steam reformer. The management of variations occurs via the industrial energy system (IES) to provide a constant load of 45 MW (a), or via the capture plant (varying reboiler load of 45 MW on average) (b). Plot c) shows the case when omitting variations in the heat sources and instead assuming annually averaged values per heat source. Adapted from [5].

Table 2: Comparison of variation management strategies via a) the industrial energy system (IES) or b) the capture plant. Case c) is when variations are omitted from the analysis (annual average). Cost assumptions are according to [5]; abs/str columns designed for 20/10 m packing, flooding approach of 80%, 95% capture (SRD ~3.86 MJ/kgCO_2); off-design performance according to model output in [11]. Capture costs are shown in €/tCO_2 avoided.

Example	Managed by	Variations [MW] min / mean / max	Reboiler [MW]	Captured [ktCO_2/a]	Capture cost [€/tCO_2]	Utilization [%]
a) IES constant load	IES	27 / 45 / 65	45	360	38.3	100
b) Varying load	Capture plant	27 / 45 / 65	27-65	384	37.7	75
c) Variations omitted	-	45 / 45 / 45	45	360	33.8	100



a) b)

Fig. 4: The cost increase of seasonal operation of the capture plant depending on the degree of plant utilization (a) and the scale (b), as compared to constant operation of the capture plant with 100% utilization to achieve the same annual level of captured CO_2. The blue dashed lines indicate the results of a generic study (13 vol.% CO_2), whereas the red single-dot describes the CO_2 capture from the blast furnace gas (24 vol.% CO_2) with heat from the CHP plant being fed together with the steel mill off-gases. Adapted from [21]

3.4. Recovery of low-temperature heat – incorporation into site-level cost curves

Although significant amounts of heat are required to regenerate the chemical solvent that absorbs CO_2, the temperature levels are relatively low (~120 °C), allowing for an efficient integration with industrial sites which often possess vast amounts of residual heat at a similar temperature. Based on a bottom-up TEA of heat supply that incorporates temporal variations described in [5], Fig. 5 illustrates site-level abatement cost curves that can help determine the most-economic degree of CO_2 capture (here: from a refinery). Fig. 5a depicts the heat supply, i.e., a mix of heat sources with minimum importation of external energy carriers (obtained via optimization). Heat sources were grouped into three classes: residual heat (heat recovered), existing capacity to generate steam (+ external energy), and new capacity to generate steam (+external energy). Fig. 5b shows the resulting heat supply cost curve and Fig. 5c the impact on the capture cost. Here, this approach is useful, *inter alia,* in identifying that:

- the heat supply cost increases with the capture rate once the potential of residual heat is exploited and external heat needs to be imported;
- areas with a flat response in cost with rising capture rates may exist;
- the economy of scale can be negatively affected by the addition of less-suitable stacks (low CO_2 concentration/flow, high level of impurities): the specific capture cost is falling with the capture rate, as expected, when capturing from the first stack. However, when less-suitable stacks are added, the specific capture cost may increase or plateau. Clustering, i.e., sharing equipment or even blending CO_2 sources, may improve this situation, albeit only to a limited extent (see [25]).

The partial capture scenarios identified with site-level cost curves can then be placed in the context of the full CCS chain, i.e., including the conditioning (which should be included into the site level cost curve but was here omitted to simplify), transport, and permanent storage of CO_2, and compared with full capture scenarios. Fig. 6 shows such contextualization for the above-mentioned refinery case. It is apparent that: 1) the heat supply for amine capture has a substantial cost impact on the full chain cost; 2) partial capture powered by recovered residual heat can lead to significant cost savings, as compared to full capture (which relies more on external energy), and these cost savings are larger than the economy-of-scale effects; and 3) heat recovery is essential for cost-efficient implementation of CCS. Furthermore, full capture will often require additional primary energy, thus leading to a cost structure that is more-sensitive to external changes in the energy system and market volatility.

To conclude, the use of detailed site-level abatement cost curves that incorporate the heat or energy supply cost based on rigorous bottom-up, techno-economic assessments can assist in identifying the most-economic degree of CO_2 capture for the implementation of CCS at industrial sites.

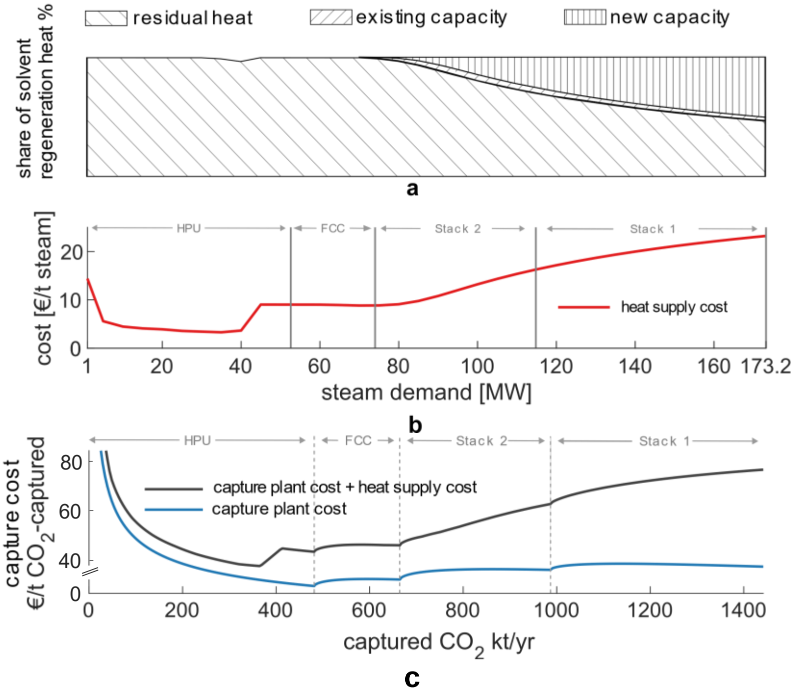
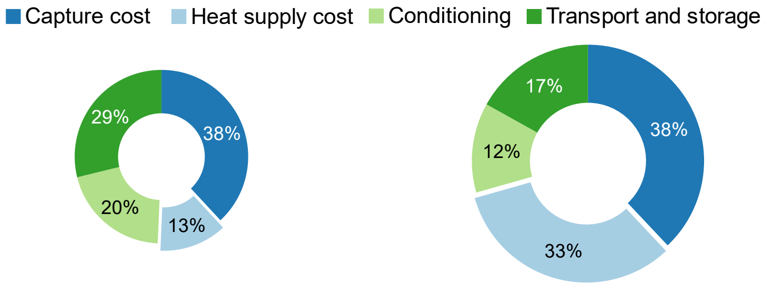


Fig. 5: Heat sources for amine solvent regeneration (a), the resulting heat supply cost curve when minimizing the external energy demand (b), and the impacts of heat supply cost on the capture cost (CAPEX & OPEX) of the amine capture plant. The capture plant costs represent one separate capture unit for each stack. Note that the abscissa is the same for panels a and b, but is different for panel c. Adapted from [5], [26]



a) partial capture - refinery
78 €/tCO_2
482 $ktCO_2$/a

b) full capture - refinery
102 €/tCO_2
1 442 $ktCO_2$/a

Fig. 6: CCS full-chain cost structure for identified partial capture scenarios as compared to a full-capture scenario b) a Swedish refinery. The partial capture scenario represents capture from a single stack – the steam reformer flue gas, while the full capture scenario represents capture from all the major stacks. Costs shown are in €2018, assuming ship transport at 7 barg to permanent storage below the seabed of the North Sea. Adapted from [5].

4. Sector-specific narratives for partial capture and remarks from a systems perspective

Ultimately, partial capture will have to lead to full capture or co-mitigation with other measures or will need to be replaced by a manufacturing technology that avoids the use of carbon entirely (CDA) by the time that the articulated climate targets shall be reached around the middle of the 21st Century. Thus, in addition to Section 3, the following aspects on timeline, alternative mitigation and policy framework will likely influence the decision to implement partial capture in the near term:

- Lead-times for the on-site implementation of CO_2 capture and conditioning units of ~4-5 years.
- Long investment cycles for manufacturing processes of typically 20-70 years that may allow only one opportunity to invest into new manufacturing processes before net-zero targets need to be reached. Although not immediately bound to these cycles as add-on technology, (partial) CO_2 capture would be affected if CO_2 or heat sources are altered by the implementation of new technology.
- The scale of the issue (e.g., the Ijmuiden steel plant with 12 Mtpa CO_2), i.e., some carbon flows are that massive that any full mitigation require time and substantial investments, likely to be introduced stepwise and over time.
- The maturity and availability at scale of alternative production/mitigation technology and associated infrastructure (electricity transmission capacity, hydrogen production/transport, natural gas/biomass access).
- The availability of CO_2 transport and storage infrastructure and the coordination with its operators.
- The need to meet EU-wide, national, and corporate near-term climate targets – often articulated for Year 2030.
- The establishment of policy frameworks, e.g., carbon contracts for difference (CCfD), and the carbon border adjustment mechanism (CBAM) which are required to trigger investments, guarantee price levels, and avoid carbon leakage in combination with the existing EU ETS. It is worth mentioning, however, that emissions allowances under the EU ETS have reached price levels that are probably sufficient to justify economically (partial) CO_2 capture. This is illustrated in Fig. 7, where the indicative full-chain cost for CCS is shown in comparison to the historic EU ETS price and a span of possible future carbon prices based on scenarios taken from the IEA World Energy Outlook 2021.

The following sector-specific narratives highlight some of the above-listed aspects.

Narrative 1 - European steel sector: The time window for partial capture at integrated steel mills (blast furnace, BF) is closing or has closed for sites that require re-investment (BF relining every 15-20 years) before Year 2030, which represent 48% of primary steel production in the EU. These sites should invest into direct-reduced iron (DRI) technology, initially using natural gas and eventually (or immediately) hydrogen from renewable/low carbon sources. The application of partial CO_2 capture in the steel industry will only be of interest for sites that: 1) remain vested in the existing BF technology because of the long investment cycles and/or cannot switch to hydrogen-based DRI immediately (hurdles may include hydrogen/renewable energy supply and ore-quality required for DRI operation [27]); and 2) want to reduce emissions from DRI operation based on hydrocarbons.

Narrative 2 – Cement: Partial capture could be combined with other mitigation options to reach net-zero emissions, including energy efficiency measures, switching to biofuels and/or kiln electrification, new cementious or less-clinker-intense products, carbonization of concrete structures during their lifetimes, and recycling of concrete. Although the first project (Brevik, Norway [28]) targets partial capture, full capture may be preferred to 1) unlock negative emissions, 2) maximize CO_2 mitigation prior to target years and minimize risk of possible delays in ramping up of co-mitigation measures.

Narrative 3 – Waste-to-energy: WtE plants could apply partial capture (SRP/ODP design) to adapt flexibly the capture rate to the energy market. For example, the capture rate can be increased during summertime when the district heating demand is low. If heat recovery allows to mitigate the fossil share of the fuel during wintertime without substantial penalties being imposed on the supply of district heating, then the increased capture rate during summertime could provide negative emissions on an annual basis. Thus, the product portfolio could be expanded to include carbon removal and to allow flexible management throughout the year depending on the regional energy and carbon markets.

Narrative 4 - Refineries: The refinery sites that have promising conditions to transition to a sustainable business model (via direct air capture, biogenic/renewable feedstock) can adopt partial capture quite cost effectively, also due to knowledgeable staff and their frequent proximity to relevant seaports. More interestingly, however, is the perspective of CO_2 capture at refineries as logical starting point for major oil companies to deploy CCS within their own corporations (Scope 1) or along their value chains (Scope 3). Oil companies, some of which have communicated ambitious net-zero goals including Scope 3, will have to apply CCS (and DACCS) or stop extracting carbon from the earth's crust altogether. Such goals could be enforced by a carbon takeback obligation (CTBO), i.e., mandatory sequestration imposed upon fossil fuel suppliers to a jurisdiction, see Jenkins et al. [29]. In a nutshell, (partial) capture from refineries (or other point sources) can be a cost-effective starting point for oil companies to mitigate in the current policy regime of EU carbon pricing and can also present a head start to get onto pathways consistent with CTBO policies if these are implemented in the future.

Final remarks from a systems perspective: Partial capture can be a piece in the puzzle to accomplish a timely transition to net-zero in the process industry. In the near-term, it can take on a share of the mitigation and relieve pressure on the electricity system and the ramping up of renewable electricity generation that is needed to expand and mitigate fossil emissions in all sectors, such as transport, residential heating, and industrial sectors. Partial capture may help to initiate the ramping up of point-source CCS, to ensure that a CO_2 transport and storage industry is established at a scale that can also handle negative emissions, which need to be created at gigatonne scale in the 21st century. A widespread, near-term implementation of partial capture would initiate large-scale mitigation and decrease the risk of new production technologies failing to arrive on time and at scale. To conclude, unless full capture or CDA manufacturing processes can be made available economically and technically in the near term, partial capture constitutes a first drastic cut in emissions, which can contribute to significantly lowering the accumulated emissions and help to meet climate targets, e.g., for Year 2030.

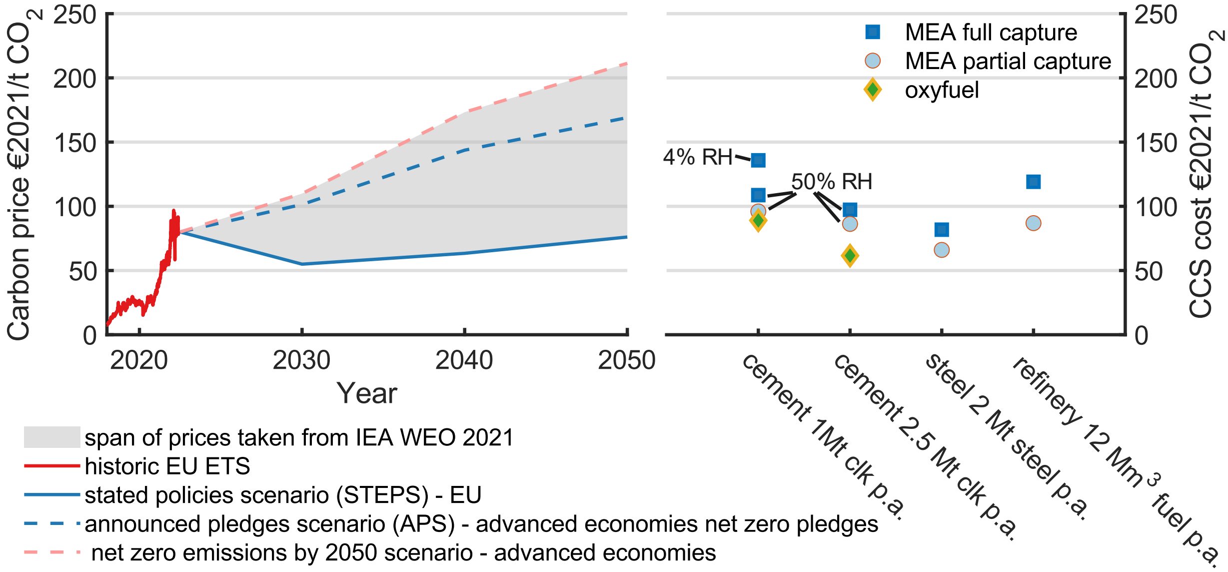


Fig. 7: Comparison of carbon prices with CCS full-chain costs from steel, refinery, and cement facilities adapted from [5],[4], and [30], respectively (techno-economic lifetime of 25 years assumed). The cost year adaption to $€_{2021}$ is based on the PCD index for CAPEX and fixed OPEX [31], the electricity and natural gas prices with the EU average prices for non-household consumers, including taxes and levies and other non-energy OPEX for the harmonized index of consumer prices. For cement, different degrees of clinker production (clk) and residual heat (RH) availability are shown. The carbon prices include historic EU ETS prices until May 2022 [32] and a span of scenario prices taken from the IEA's World Energy Outlook 2021 [33].

5. Conclusions

This paper gives a review of aspects to consider for a cost-effective and timely CCS implementation in process industry via partial CO_2 capture. Techno-economic and policy-related aspects relevant to the facilitation of near-term implementation of carbon capture are elaborated, with the focus on the site-level perspective. The findings emphasize that partial capture can imply a cost-effective implementation of CCS, which is paramount in the following aspects:

- Energy and cost-effective design of partial capture
- Potential energy and cost savings when operating off-design at lower separation rates.
- The ability to cope with temporal variations, e.g., in heat supply, via a proper capture process design or via the industrial energy system.
- Extensive heat integration to minimize costs and emissions from the import of additional energy carriers to power the capture unit.
- Policy instruments that incentivize investments into emissions reduction, for example, clarify the allocation of carbon emissions reductions to low-carbon products to create consumer related mechanisms.
- The recognition of the narrow window of opportunity of ~30 years for partial capture in line with the climate targets of the Paris Agreement.

In conclusion, partial capture of CO_2 is a readily available and economically viable mitigation option for process industry. Implementation before Year 2030 could help to achieve the reduction targets for Year 2030 articulated at a corporate/national level, and would provide a response to the required initiation of large-scale emissions reductions via CCS in line with the aspiration of a 1.5°C or 2.0°C global warming limit.

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