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Accounting for carbon capture solvent cost and energy demand in the energy system

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Abstract

Technical carbon dioxide removal through bioenergy with carbon capture or direct air capture (DAC) plays a role in virtually all climate mitigation scenarios. Both of these technologies rely on the use of chemical solvents or sorbents in order to capture CO_2. Lately, concerns have surfaced about the cost and energy implications of producing solvents and sorbents at scale. Here, we show that the production of chemical sorbents could have significant implications on system cost, energy use and material use depending on how much they are consumed. Among the three chemical sorbents investigated, namely monoethanolamine (MEA) for post-combustion carbon capture, potassium hydroxide (KOH) for liquid DAC and polyethylenimine-silica (PEI) for solid sorbent DAC, we found that solid sorbent production for DAC represents the highest uncertainties for the system. At the high range of solid sorbent consumption, total energy system cost increased by up to 6.5%, while effects for other options were small to negligible. Scale-up of material production capacities was also substantial for MEA and PEI. While PEI has the advantage of requiring a lower sorbent regeneration temperature than KOH, the potential production cost may outweigh these benefits. There is thus a trade-off between the advantages and the additional cost uncertainty regarding sorbents. Implications of sorbent consumption for carbon capture technologies should be considered more thoroughly in scenarios relying on solid sorbent DAC.

1. Introduction

Carbon capture plays a key role in virtually all climate mitigation scenarios limiting the global mean temperature increase to 1.5 °C and 2 °C compared to pre-industrial levels [1]. Captured carbon can be sequestered (carbon capture and storage, CCS) to avoid fossil emissions to the atmosphere, or to provide carbon dioxide removal if the carbon stems from biomass (bioenergy with carbon capture and storage, BECCS) or direct air capture (DAC). Alternatively, utilisation of captured carbon (CCU) provides raw material for the production of fuels and chemicals and contributes to increasing the carbon efficiency of scarce biogenic carbon [2]. In the IPCC illustrative mitigation pathways that limit global warming to 2 °C or below, between 168–763 $GtCO_2$ and 0–339 $GtCO_2$ are sequestered in this century through BECCS and DACCS, respectively [1], corresponding to an annual average of 6%–26% and 0%–11% of 2024 global CO_2 emissions [3]. Studies with sector-coupled energy system models also include CCU and reach 1–6 Gt annual carbon capture by the mid-century globally [4, 5], while studies focusing on Europe arrive at 0.4–2.2 Gt [2, 6, 7]. The role of carbon capture thus varies dramatically.

Carbon capture encompasses two main pathways: point-source, including post-combustion and pre-combustion capture, and DAC. In post-combustion capture, solvents are used to absorb CO_2 from the flue gases. The solvent is then regenerated by supplying heat that unbinds the chemicals. In its lifetime, the solvent is degraded mainly by oxidation with oxygen or acid gases present in the flue gas,

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which is catalysed by the heat of the regeneration [8–10]. In pre-combustion capture, the fuel carbon content is removed and captured with a solvent, in processes such as steam methane reforming, gasification of solid fuels, or biogas upgrading to biomethane.

By DAC, CO_2 is captured from the atmosphere by passing ambient air through a contactor and absorbing CO_2 [8]. Key technologies are L-DAC, using a liquid solvent and high temperature heat for regeneration, and S-DAC, using a solid sorbent and low temperature heat (S-DAC). L-DAC is based on sodium (KOH) or potassium hydroxide (NaOH) capturing CO_2 from the atmosphere. The solvent consumption is mainly caused by absorber losses through aerosol formation and spray drift [11, 12]. S-DAC captures carbon with the use of temperature-swing adsorption and a solid chemical adsorbent [13]. During S-DAC operation, the solid sorbent is also progressively degraded through exposure to ambient conditions such as sunlight, temperature, humidity or particulate matter, as well as the successions of loadings and unloadings that it undergoes. All sorbents degrade differently and understanding the phenomena is subject to continued research [14].

Despite their advanced technological development, with a technological readiness level of 9 for post- and pre-combustion, and 7 for DAC [8], carbon capture technologies have yet to be proven at scale. 51 Mt carbon capture capacity is in place in 2024, mainly in fossil applications for enhanced oil recovery [15], while 30 Mt BECC [16] and 65 Mt DAC [17] are in planning worldwide. Besides expansion challenges [18], high cost, energy demand, and resource limitations [2], carbon capture requires the use of solvents or sorbents which capture CO_2 from either syngas (pre-combustion), flue gases (post-combustion), or from the atmosphere (direct air capture, DAC).

While solvents for post-combustion carbon capture have been proven at commercial scale, solvents and sorbents for DAC have been less researched and deployed. Uncertainties regarding costs [19, 20] as well as energy and material requirements [21] related to solvents and sorbents are substantial. For example, Chatterjee and Huang [21] estimated that the energy demand of material production and solvent regeneration alone may amount to 12%–20% and 34%–51% of global energy demand, respectively, signaling that these aspects deserve a closer analysis.

Despite the large role of carbon capture in mitigation scenarios, uncertainties regarding solvents have thus far received little attention, and costs and energy use of solvent production have not explicitly been taken into account in such studies. This study aims to quantify the effect of carbon capture solvent and sorbent cost and energy use uncertainties on the cost-competitiveness of carbon capture technologies and on energy system cost.

2. Methods

2.1. Data

This study focuses on three different carbon capture technologies: post-combustion carbon capture using a monoethanolamine (MEA) solvent; L-DAC, a high-temperature DAC using the liquid solvent KOH; and S-DAC, a low-temperature DAC using a polyethylenimine (PEI) on silica solid sorbent. These solvents and sorbents were chosen based on three main criteria: accessibility of materials used for production (to decrease otherwise high uncertainty), availability of data associated with their production, and their prevalence in concrete plans or studies. The solvent and sorbent production methods were estimated based on currently available technologies (figure 1).

Economical input parameters for S-DAC and L-DAC, such as capital expenditure (CAPEX) and operational expenditure (OPEX) (except those related to solvent and sorbent consumption) account for technological learning and economies of scale for a total scale of 1 Gt of global carbon capture capacity, based on Young *et al* [19]. Post-combustion carbon capture data were obtained from the Danish Energy Agency database [22]. The provision and consumption of solvents or sorbents are isolated from the other costs and considered separately in the analysis.

In this work, an optimistic and a pessimistic scenario represent the lower and the higher bounds for costs and energy use. Post-combustion MEA consumption ranges between 0.27–3.98 kg/t_{CO_2} [23]. Const$_{CO_2}$umption values of KOH for L-DAC range between 0.4 kg/t_{CO_2} [12, 24] and 38 kg/t_{CO_2} [25] and are assumed to represent the value range. S-DAC sorbent consumption ranges between 2.3–14 kg/t_{CO_2}, based on an estimated lifetime range of 0.5–3 years [25]. Another estimate based on data from Climeworks of 3–7.5 kg/t_{CO_2} [14] falls within this range, although the full range of 2.3–14 kg/t_{CO_2} is used in this work to represent the uncertainty.

MEA is produced via the reaction of ethylene oxide and ammonia in the ethanolamine production process [26]. KOH is the result of the electrolysis of brine (water and KCl) [27]. PEI is produced from the reaction of an ethanolamine with sulfuric acid in the Wenker process, leading to aziridine, followed by a second reaction involving, among other chemicals, sodium or KOH . Finally, PEI, being the sorbent active phase, is deposited on silica gel, the latter acting as the support which helps the active phase to increase its contact surface with the air [14, 28].

Black-box process data (feedstock inputs, outputs, conversion efficiencies) and economic

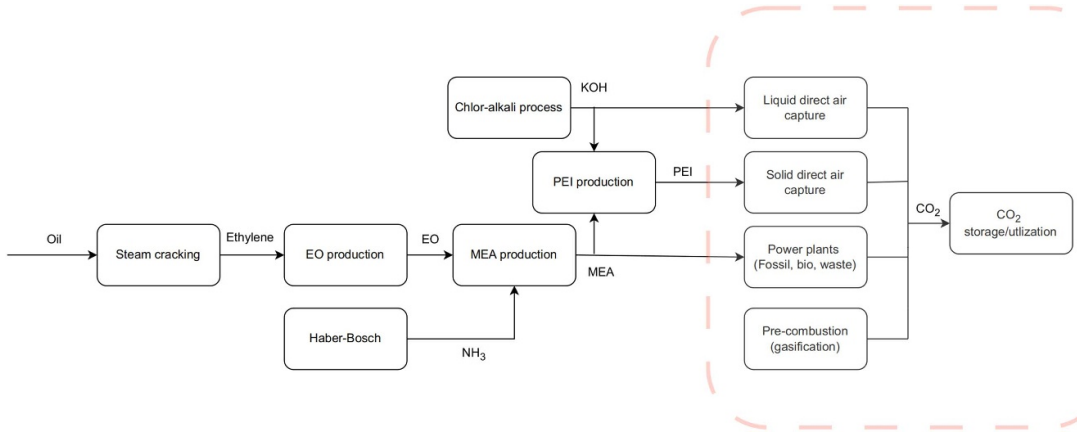

Figure 1. Model representation of solvent and sorbent production in this study. The base version with less detail is highlighted by the dashed box. Abbreviations: EO = ethylene oxide, KOH = potassium hydroxide, MEA = monoethanolamine, PEI = polyethylenimine.

assumptions are detailed for all carbon capture related technologies in the supplementary information.

2.2. Model

PyPSA-Eur-Sec [29, 30] is an open-source, sector-coupled European energy system optimisation model including the power sector, transport (including also international shipping and aviation), space and water heating, industry and industrial feedstocks. The model minimises total system costs by co-optimising capacity expansion and operation of all energy generation and conversion, as well as of storage and transmission of electricity, hydrogen and gas. The model is based on the Python software toolbox PyPSA (Python for Power Systems Analysis) [31]. A comprehensive description of the model can be found in Neumann *et al* [32]. A version with an extended biomass and technology portfolio is used [2, 33].

A 37-node spatial resolution and a 5-hourly temporal resolution over a full year in overnight greenfield scenarios was used. A lossy transport model for electricity transmission was used which is suitable at this resolution [34], and transmission is constrained to expand to at most double the total line volume in 2022.

Final energy demands for the different sectors are calculated based on the JRC IDEES database [35] with additions for non-EU countries (see [30, 36] for further elaboration), and need to be met (i.e. demand is perfectly inelastic). However, energy carrier production including electricity, hydrogen, methane and liquid fuels is determined endogenously. Fossil fuels (coal, natural gas and oil) as well as uranium are included, as are solid biomass imports as outlined below. Technology costs and efficiencies are elaborated on in the supplementary information, with technology values for 2040 (given in $€_{2015}$) used from the PyPSA energy system technology data set v0.6.0 [37]. The discount rate is uniform across countries and set to 7%, except for rooftop solar PV and decentral space/water heating technologies, for which it is set to 4%.

2.3. Scenarios

In the scenarios, three factors are varied, based on their effect on carbon capture and large span in climate mitigation scenarios, resulting in eight main scenario combinations: fossil fuel usage, biomass availability, and emission target.

Climate mitigation scenarios differ considerably in how much fossil fuels are used, which has a strong impact on the utilisation of CCS and CCU for achieving targets. Some scenarios rely heavily on CCS which allows substantial amounts of fossil fuels to be used, while others assess 100% renewable energy systems in which case more CCU is used. In order to represent both of these approaches, scenarios both including and excluding fossil fuels are explored.

Previous assessments also differ strongly in the assumed biomass availability. Therefore, scenarios with only domestic residues from the JRC ENSPRESO medium scenario [38] and ones including also biomass imports are explored. Biomass imports are assumed to represent a carbon neutral resource with a substantially higher price [2], which could in principle also be supplied by extending the use of domestic resources.

The European Union aims to become the first continent to reach net zero emissions across all sectors and to do so by 2050 [39]. Net-negative targets in the energy system may be needed to offset hard-to-abate emissions from, for instance, agriculture, as well as to compensate for historic emissions [5]. Therefore, net-zero and −110% net-negative emissions targets are analysed.

In order to better be able to compare with previous model assessments which thus far mostly do not include L-DAC, these 8 scenarios are explored in

cases where L-DAC is included and excluded, with both pessimistic and optimistic solvent and sorbent assumptions.

2.4. Cost assessment

As a method of comparing the effects that implementation of solvent and sorbent production has on the cost of carbon capture systems, their levelized cost of carbon (LCOC) with and without accounting for solvents are compared. This metric represents the cost of capturing one unit of CO_2. For DAC plants, the LCOC is calculated according to equation (1).

$$\mathrm{LCOC_{DAC}} = \frac{\mathrm{CAPEX}\cdot(\mathrm{CRF}+F_{\mathrm{OM}})}{8760\cdot C_f} + V_{\mathrm{OM}} + \delta_{\mathrm{el}}\cdot p_{\mathrm{el}} + \delta_{\mathrm{H}}\cdot p_{\mathrm{th}} \quad (1)$$

CAPEX is the capital cost of the investment in €/$t_{\mathrm{CO2captured}}$. It is annualised using a capital recovery factor (equation (2)). F_{OM} is the fixed operations and maintenance cost [% of CAPEX /year], 8760 the number of hours per year, C_f is the capacity factor [%], V_{OM} is the variable operations and maintenance cost in [€/$t_{\mathrm{CO2captured}}$], which excludes the cost of energy and solvent regeneration, δ_{el} and δ_{H} are the heat and the electricity demands [MWh/$t_{\mathrm{CO2captured}}$], and p_{el} and p_{th} are the electricity and the heat prices [€/MWh]. In the impact assessment, the solvent production cost is added to the V_{OM}.

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

where i represents the discount rate [%/year] and n the lifetime of the plant [years].

For power plants performing carbon capture, the LCOC ($\mathrm{LCOC_{pp}}$) is calculated as the levelised cost of energy (LCOE) difference with carbon capture, $\mathrm{LCOE_{CC}}$, and without it, $\mathrm{LCOE_{NoCC}}$ [€/$\mathrm{MWh_{output}}$], divided by the amount of carbon captured by the plant η_{cc} [$t_{\mathrm{CO_2}}$/$\mathrm{MWh_{output}}$] [8] (equation (3)).

$$\mathrm{LCOC_{pp}} = \frac{\mathrm{LCOE_{CC}} - \mathrm{LCOE_{NoCC}}}{\eta_{\mathrm{cc}}} \quad (3)$$

The LCOE of a power plant measures the cost of producing one unit of energy [8] (equation (4)).

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX}\cdot(\mathrm{CRF}+F_{\mathrm{OM}})}{8760\cdot C_f} + V_{\mathrm{OM}} + \frac{C_{\mathrm{fuel}}}{\eta} \quad (4)$$

C_{fuel} is the fuel cost (€/$\mathrm{MW_{th}}$) and η is the conversion efficiency of the plant. For power plants producing both heat and electricity, the LCOE is calculated per unit of total energy output. Therefore, $\eta = \eta_{\mathrm{el}} + \eta_{\mathrm{th}}$.

3. Results and discussion

The system effect of accounting for solvent costs and energy use is threefold: first, the specific energy input differs for the various solvents; second, solvent replenishment rates are subject to large uncertainties, leading to large variances in costs and energy use; third, the deployment of different carbon capture options affects the cost contribution of solvents and sorbents.

The specific energy inputs of solvent and sorbent production vary substantially (figure 2). MEA requires a large amount of oil due to its synthesis requiring ethylene, which is a petroleum derivative mainly produced from steam cracking of naphtha or ethane today [40]. The oil source differs substantially in the scenarios: it is fossil if compensation by negative emissions elsewhere is possible; otherwise it is dominated by e-fuels if biomass is limited, or by biofuels if not. MEA is further used in the amine-silica sorbent synthesis, transmitting the high oil consumption. The Chlor-alkali process involved in producing KOH requires electricity input, but the overall energy requirement remains substantially lower than for the two other solvents, and hydrogen emerges as a by-product.

The effect of accounting for solvent production uncertainty on LCOC (figure 3) and energy consumption (figure 4) differs between the three technologies, which affects their relative cost-competitiveness. While solvents contribute only marginally to the cost of post-combustion and L-DAC, by 6 €/$t_{\mathrm{CO_2}}$ (11%) and 14 €/$t_{\mathrm{CO_2}}$ (6%), respectively, S-DAC sorbents contribute to up to 55 €/$t_{\mathrm{CO_2}}$ (18%) of LCOC and up to 0.3 MWh/$t_{\mathrm{CO_2}}$ (13%) of energy consumption. Thereby, the cost advantage of L-DAC is further enhanced. If solvent and sorbent consumption falls in the optimistic range, effects on LCOC and energy use are small to negligible for all carbon capture options.

In addition to the specific impacts on the technologies, the overall system effects also depend on the magnitude of deployment of the different carbon capture options. Figure 5 illustrates the usage of each carbon capture technology in the model results for the net-zero (N0) and net-negative (NN) scenarios, with (Im) and without biomass imports (NoIm) and with (FF) and without fossil fuels (NoFF).

Carbon capture deployment exhibits a large variation between scenarios, ranging between 330 $MtCO_2$ in a net-zero scenario where fossil fuels are completely phased out (N0-Im-NoFF), and 2005 $MtCO_2$ in a net-negative scenario including fossil fuels (NN-NoIm-FF). If biomass is readily available (Im), post- and pre-combustion carbon capture dominate (figure 5), with a negligible effect (0%–0.63%) and (0%–0.37%) of solvent production on system costs and energy use, respectively. However, if biomass is limited to medium domestic residue potentials only (NoIm),

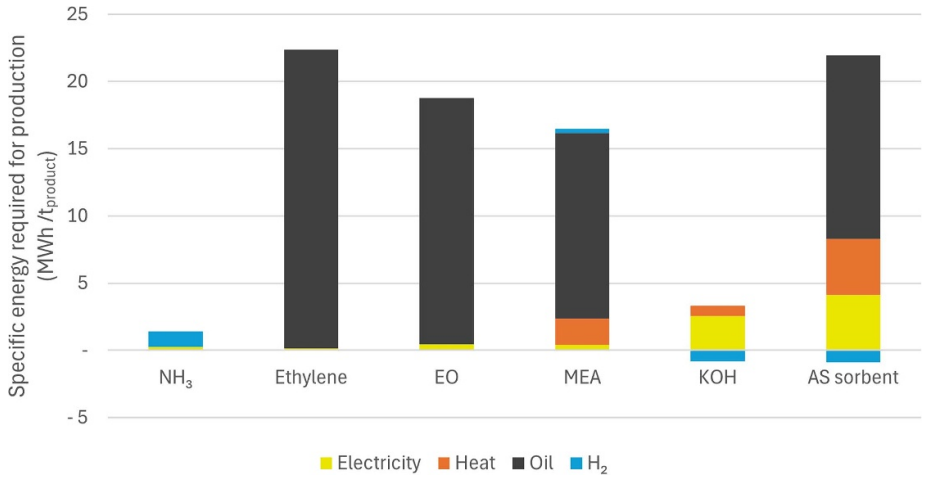

Figure 2. Specific energy requirement for carbon capture solvent and sorbent production. The bars account for the whole, cumulative production chain, including energy to produce each feedstock. For example, for MEA, the energy to produce EO and NH_3, weighted by their shares in producing MEA, is included in addition to the energy consumption for the MEA process itself. The oil source (fossil, biofuel or e-fuel) is determined endogenously in the model. NH_3 = ammonia, EO = Ethylene oxide, MEA = Monoethanolamine, KOH = Potassium hydroxide, AS sorbent = Amine (PEI) -silica solid sorbent.

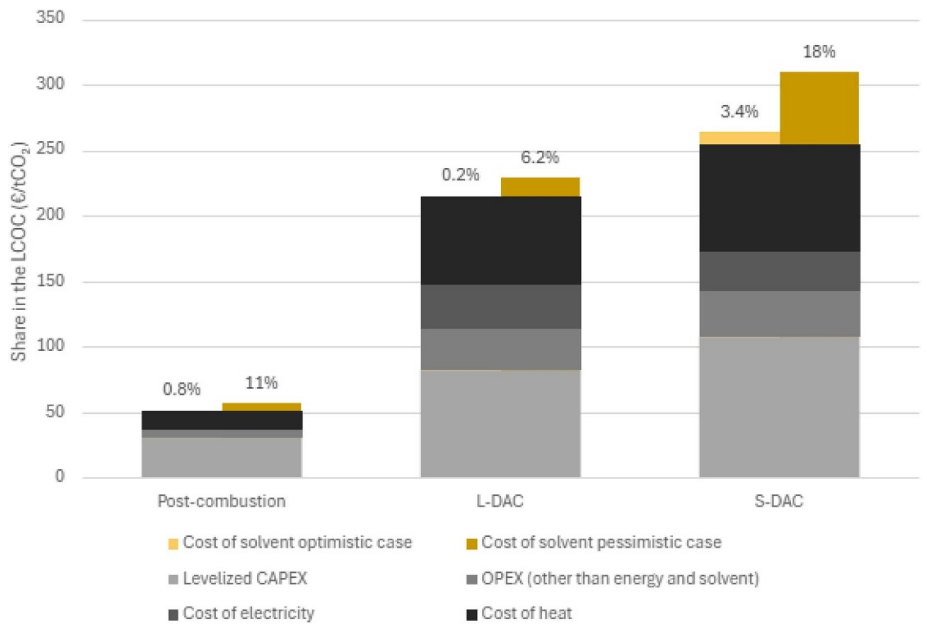

Figure 3. Levelised cost of carbon (LCOC) breakdown for each carbon capture technology. For post-combustion, only the carbon capture infrastructure capital cost (CAPEX) is included, as carbon is considered a by-product. In addition, carbon capture process heat cost and operational expenditure (OPEX) is included. Since there are several post-combustion processes in the model, the baseline LCOC for this technology, without solvents, is determined by averaging the LCOCs calculated for each of them. Abbreviations: DAC = direct air capture, either with liquid solvent (L) or solid sorbent (S).

DAC is used to supply carbon for fuel production (CCU) in the non-fossil (NoFF) scenario, or for negative emissions (CCS) if fossil fuels are allowed (FF). In the latter case, more carbon capture cost-effectively compensates for fossil emissions, and thus, because more solvents are used, the effect of solvents is larger than in the non-fossil scenarios.

Of the two DAC options, L-DAC is more cost-competitive, and L-DAC solvents present little challenges for the energy system, with solvent production contributing to at most 0.9% of the total energy system cost and to 0.4% of energy demand (figure 6), despite a large deployment of carbon capture in the net-zero scenario including fossil fuels (N0-NoIm-FF), at 1592 $GtCO_2$/y. Thus, production of KOH for L-DAC and MEA for post-combustion does not represent a challenge for large scale carbon capture deployment.

Conversely, if S-DAC is provided as the sole DAC option (as is often the case in many ESM studies [2, 6, 7]), the system is more evidently affected by sorbent uncertainties. In this case, in scenarios with

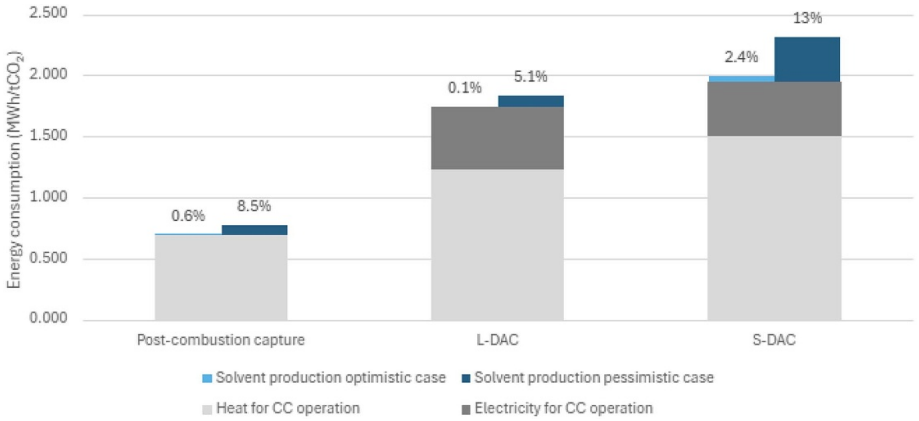

Figure 4. Energy consumption breakdown for each carbon capture technology. Abbreviations: CC = carbon capture.

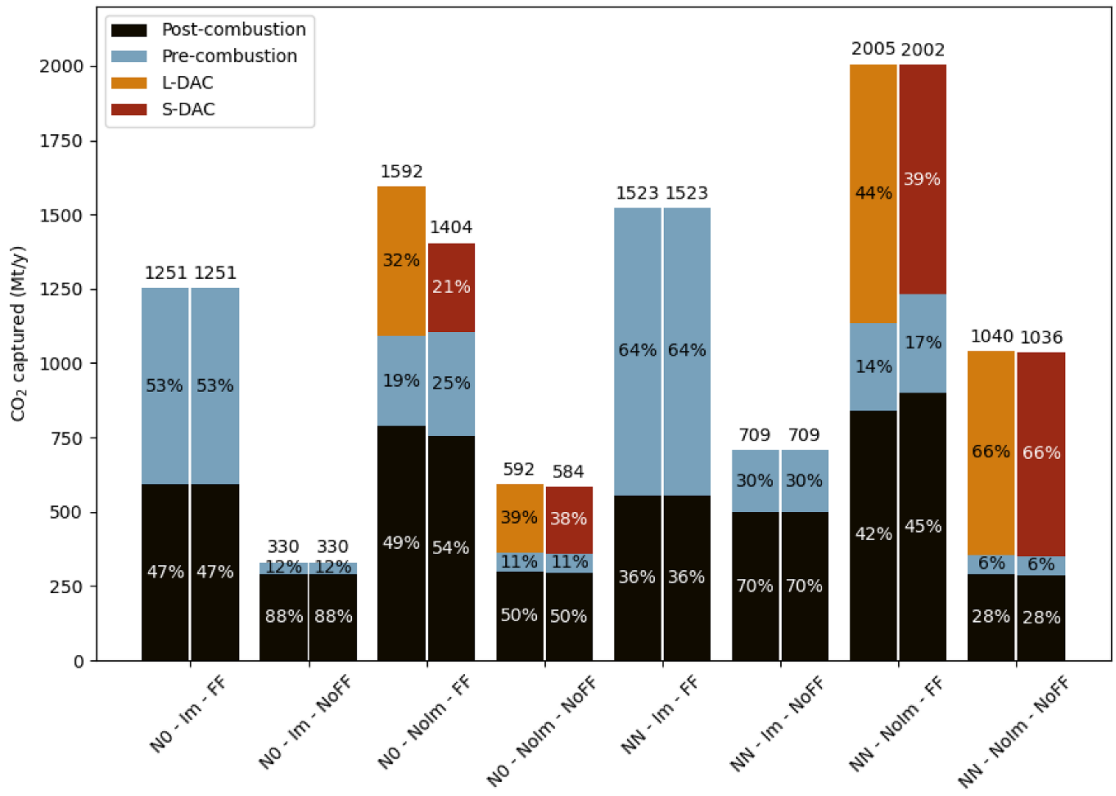

Figure 5. Amount of CO_2 captured in Europe by each technology type in the model results. For each scenario, the left hand side bars represent the case where both L-DAC and S-DAC are included, and the right hand side bars show results with S-DAC as the only DAC option. As the capacities of these processes barely change between the base case and the case with solvent production, only the base case status is presented here. The labels represent the different scenarios: N0 = Net zero emission target, NN = Net negative, Im = with import of biomass, NoIm = No import of biomass, FF = Fossil fuels included, NoFF = No fossil fuels.

negative emissions and limited biomass, the total system cost contribution from solvent and sorbent production alone amounts to 5.4%–6.5% (up to 52 billion €) and the energy demand contribution from solvent and sorbent production ends up at 1.8%–2.8%.

The main reason for the wide S-DAC sorbent cost range is the uncertain replacement rate. While L-DAC solvents have been tested on an industrial scale in the Kraft pulping process, which narrows down the uncertainty also for L-DAC usage [11, 25, 41, 42], S-DAC sorbent degradation is still poorly understood [14].

DAC is a novel technology with a technology readiness level of 6–7, and thus the processes have yet to be tested on a large scale. This study assumes a PEI-silica sorbent but other proprietary sorbents under development might perform better. The results indicate that there is a strong cost incentive to develop sorbents that efficiently capture carbon

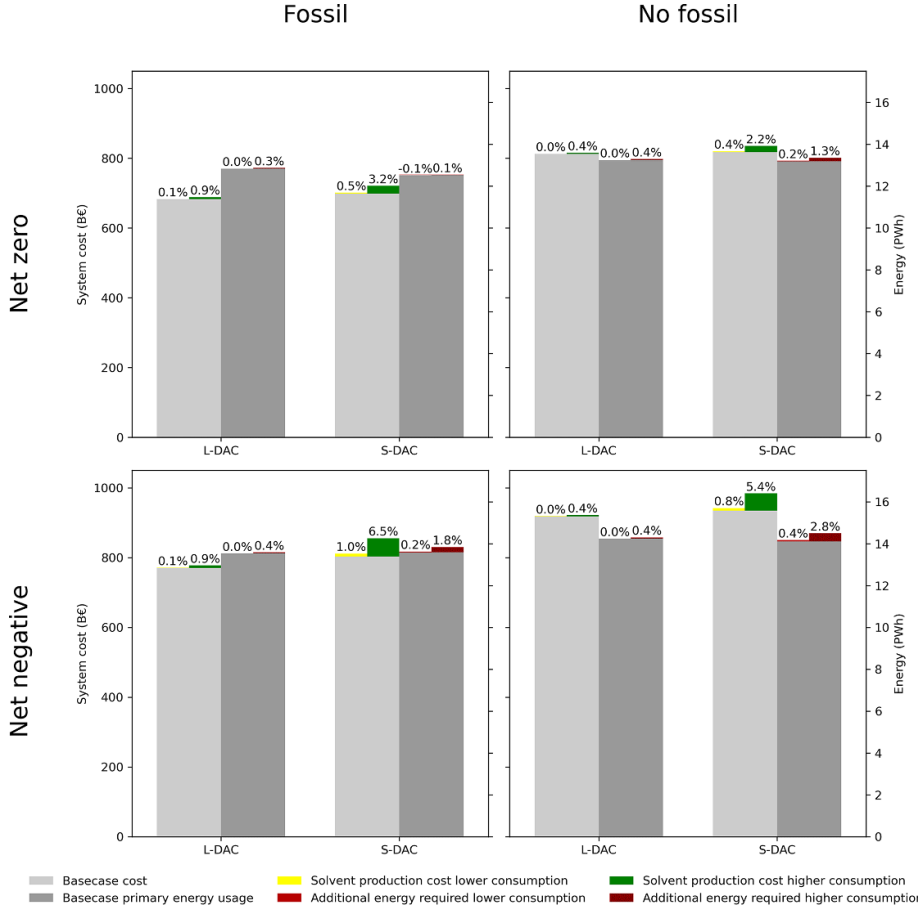

Figure 6. Impacts on the energy system of accounting for carbon capture solvent and sorbent production. Scenarios with limited biomass availability (NoIm) are shown. The variations presented are the differences between the total system cost (yellow and green bars) and total system primary energy consumption (red bars), which includes fossil fuels, biomass and renewable electricity. Negative differences might occur in cases where the most-cost optimal system after solvent production implementation requires less primary energy than in the base case, as in the N0-NoIm-FF scenario.

and are resistant to degradation, but there is also a trade-off between sorbent reactivity, robustness, and production cost. A review article by Zhu *et al* [43]. highlights many of the complexities involved. For instance, shorter aminopolymer sorbents may have higher reactivity, but also lower thermal stability than longer chains. Moreover, moisture may enhance CO_2 adsorption capacity but also contribute to structural degradation and a higher regeneration energy requirement. The pore structure of the support combined with how the sorbent attaches to it also affects efficiency and stability. Factors such as chain length and structure, amine dispersal in the pores and support resistance to different conditions regarding moisture and heat affect overall performance. There is also an economic trade-off, as some siliceous supports exhibiting desirable properties are also costly. Another important determining factor of adsorbent lifetime is oxidative stability. All of these aspects are subject to continued research.

Although solvent production for carbon capture may require a substantial scale-up of production capacities (table 1), the high material demand estimated by Chatterjee and Huang [21] could not be confirmed (figure 7), due to much lower solvent and sorbent consumption and much more efficient MEA production even in the pessimistic case. While ethylene, ethylene oxide and ammonia are already produced in much higher quantities than are demanded in the scenarios, the production of MEA and KOH may need to scale up by more than one order of magnitude, should global demand develop similarly to the obtained European demands. This is however little compared to the capacity expansion of other technologies such as solar PV, wind power or electrolysis in the assessed scenarios. For PEI, on the other hand, no large-scale production capacity exists today (table 1), which could present a bottleneck and a supply uncertainty in the expansion phase of S-DAC. Polymeric materials similar to PEI are however produced in large quantities globally, suggesting that such an expansion is feasible. The scale-up of KOH and NaOH should present little challenges [25], as they are derived from KCl and NaCl salts that are very abundant on Earth, and rely on the Chlor-Alkali process (electrolysis of brine), which is a common industrial process.

Table 1. Material requirement for the lower and the higher solvent consumption. The values are the highest material usage across all assessed scenarios.

Material req. (Mt/y)	MEA	KOH	PEI	EO	Ethylene	NH_3
Optimistic case	2	2.1	0.9	1.5	1.3	2.6
Pessimistic case	14.4	27.5	5.4	10.8	8.9	18.6
Global production	2.5[a] [14]	9[b] [44]	0.01 [14]	31 [45]	225 [46]	240 [47]

[a] Global production of all three EAs.

[b] For NaOH, the global production is of 82 Mt/y [48].

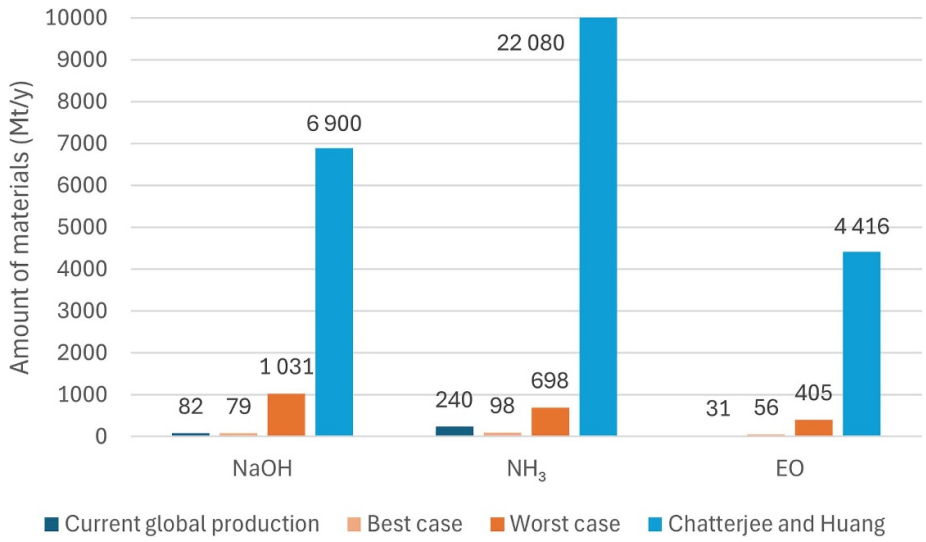

Figure 7. Projected material demand in the case of a DAC scale-up to 30 $GtCO_2$/y, based on assumptions in this study compared to Chhatterjee and Huang [21] and current global production [45, 47, 48].

DAC costs are subject to large uncertainties in the literature, resulting in overlapping cost projections for different DAC options [19]. Some studies have projected lower costs for S-DAC than for L-DAC, mainly due to the lower temperature heat demand allowing for waste heat usage [49], but other studies find that sorbent cost drives the opposite outcome [50].

While S-DAC has a larger disadvantage compared to L-DAC regarding both cost and energy use when it comes to sorbent and solvent production, L-DAC has other challenges. In particular, it requires about 900 °C heat input [11] for solvent regeneration compared to about 100 °C for S-DAC [13]. L-DAC therefore needs a heat source utilising methane (as assumed in this study), hydrogen or possibly electricity [51], while S-DAC can use less costly options such as waste heat from industry (to the extent that this limited resource is available) [19], geothermal heat as used by Climeworks Orca and Mammoth plants in Iceland [52, 53], or industrial heat pumps [54, 55]. Moreover, from a life-cycle perspective, L-DAC has been found to have a higher environmental footprint than S-DAC if natural gas is assumed for heat supply and due to the displacement of substantial mass flows in the process [25]. L-DAC also consumes significant amounts of fresh water due to evaporation of the diluted solvent in contact with air and requires up to 6 times more land area than S-DAC to implement its bulky infrastructures [25, 56]. Conversely, S-DAC uses dry sorbents and its modular infrastructure makes it less area intensive [25].

Energy system studies commonly have included S-DAC as the sole DAC option [2, 6, 7], with the advantage that the heat source can be supplied by low-cost waste heat or through heat pumps [49]. This study finds that S-DAC sorbent induced energy system cost uncertainties are substantial, and thus presents a trade-off with the more flexible heat source which has been mentioned as a strong argument for S-DAC.

3.1. Limitations

The choice of solvents and sorbents studied in this model was dependent on available data. For sorbents especially, there are multiple options being considered for use, and price forecasts exhibit large variations [12, 19, 20, 57], with spans exceeding the costs assumed in this study, which may therefore even be underestimated.

Solvents associated with pre-combustion were excluded from the study as reports suggest that the degradation of solvents used in this technology is minimal [23]. Alternative CCS technologies

such as oxy-fuel combustion, chemical looping, and membrane options were not considered as they generally avoid the use of solvents or sorbents and exhibit lower technology readiness levels.

4. Conclusions

Although carbon capture costs remain dominated by capital and operational energy expenditures, solvent cost may be significant, especially for solid sorbent DAC. The cost and energy use uncertainty of solvents for post-combustion carbon capture as well as L-DAC and S-DAC was assessed and was found to affect their internal cost-competitiveness and potentially increase energy system cost significantly. For post-combustion carbon capture and L-DAC, solvent uncertainties present negligible challenges on the energy systems level. In contrast, S-DAC solvent uncertainties were found to represent a share in LCOC of up to 18%, and contribute to total energy systems cost by as much as 6.5% (52 billion €) in net-negative (−110%) scenarios. Solid sorbent degradation and replacement accounts for large cost uncertainties, providing strong incentives to develop robust sorbents which are still reactive and affordable. Scale-up of solvent and sorbent production was estimated to be uncritical compared to the observed scale-up of many other technologies such as solar PV, wind power and electrolysers.

S-DAC is modular and therefore more flexible in terms of unit size, requires lower temperature heat to regenerate the sorbent, and it has potentially lower environmental impact, which offers advantages compared to L-DAC. There is thus a trade-off between these advantages and the additional cost uncertainty regarding sorbents.

Energy system modelling studies have thus far not included details on sorbents and solvents but large amounts of carbon capture are obtained in climate mitigation scenarios. While this was found to be uncritical for post-combustion carbon capture, uncertainties especially for S-DAC are substantial and need to be considered in modelling assessments. This is an issue especially in climate mitigation scenarios with low biomass availability and where S-DAC plays a large role, in which case sorbent-induced cost uncertainties are the largest.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Code availability

The code used can be found at https://github.com/humpage/pypsa-eur-sec/tree/solvent

Technology data used can be found at https://github.com/humpage/technology-data/tree/biopower

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