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# Techno-economic analysis of innovative carbon capture and storage chains

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**Abstract**

To work in line with the Paris Agreement targets of keeping global temperature increase below 1.5°C, rapid emissions reductions and large-scale carbon dioxide removal (CDR) are necessary [1]. Carbon capture and storage (CCS) is one of the main technological pathways that can achieve deep emissions reduction. Post-combustion CCS technologies can be applied at existing sites without major modifications to existing processes, making it a mitigation option that is relatively easy to implement as an end-of-pipe solution. In addition to mitigating fossil $CO_2$ emissions, CCS can contribute to CDR via bioenergy with CCS (BECCS) from for instance pulp and paper plants, waste incineration plants or bio-fired heat and power plants. Put together, these factors make CCS technologies highly relevant for both fossil $CO_2$ mitigation and carbon dioxide removal, and thus, the aim of transitioning to a low-$CO_2$ emissions economy.

To enable cost-effective implementation of CCS technologies, different technologies and systems need to be evaluated and compared, and their roles in different regions and sectors need to be assessed. Several previous works have performed cost estimates of CCS technologies, typically assuming that technologies are mature, estimating n$^{th}$-of-a-kind (NOAK) cost. While some works have estimated first-of-a-kind (FOAK) costs (e.g., [2], [3]), additional comparison between benchmark and novel technologies considering the transition from FOAK to NOAK costs are needed. This is important as different technologies are at different stages of maturity and their future costs can be expected to differ significantly as a result of learning by implementation and research. Furthermore, most studies that assess future costs do so only by analyzing the expected decrease in CAPEX due to learning by implementation and research. Although this is certainly a key factor, other factors also have a significant impact. Energy and material efficiency are expected to improve over time, leading to cost reductions. External factors such as the evolution of prices and emissions of energy (power and heat) as a result of the European transition to net-zero also significantly affect economic performance. Thus, the aim of this work is to include all these effects to provide a comprehensive possible outlook into future costs for the complete CCUS chain.

The scope of this work is to cover the full CCUS chain, from capture to storage or utilization, considering benchmark technologies as well as innovative technologies. Here, innovative technologies refer to technologies that are currently at a lower technology readiness level (TRL) than their benchmark counterparts, but are nonetheless of interest to investigate due to their potential to decrease cost. The considered benchmark technologies for $CO_2$ capture are absorption using MEA (30wt%) or AMP-PZ (40 wt% PZ/AMP solution in 1–2 M ratio). In addition, membrane separation (e.g., Polaris membranes by MTR) and pressure swing

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adsorption (using different adsorbent such as zeolite13X or relevant metal organic frameworks) are investigated. For transportation, liquid $CO_2$ at 7 barg and 15 barg (for bulk transport, e.g., trucks and ships) as well as high-pressure dense phase $CO_2$ (for continuous pipeline transport) are considered as alternatives. For $CO_2$ storage, permanent storage in saline aquifers or depleted oil and gas fields is investigated.

The technologies considered are applied to case study CCUS chains in the waste-to-energy (WtE), cement, pulp and paper, and (bio)refinery sector. The waste-to-energy case considers the KVA Linth WtE plant in Niederurnen, Switzerland, with annual emissions of around 200 $ktCO_2$/year. Two cement plants owned by Heidelberg Materials are included, one located in Hannover, Germany and one located in Górażdże, Poland, with emissions of 700 and 3600 $ktCO_2$/year, respectively. The pulp and paper case considers a pulp mill owned by Stora Enso located in Skutskär, Sweden with emissions of 1100 $ktCO_2$/year. The (bio)refinery studied is based on one of TotalEnergies OneTech existing biorefineries. It is a formerly conventional refinery now converted to biorefinery and it is called "Horizon" (HBR) for the purposes of this study. HBR's $CO_2$ emissions are 230 kt/year.

To perform the analysis, this work builds upon previous methodological approaches and results from the ACCSESS project [3]. FOAK costs are calculated using techno-economic analysis tools for the technologies considered in the case study chains. The FOAK costs are used in a model developed in this work that allows FOAK costs to be extrapolated to future expected costs based on assumed learning rates and regional conditions, e.g., electricity and fuel price developments. The model will be made publicly available upon publication of the work, to allow for further investigations into time-resolved technology comparison. Figure 1 shows an exemplification of results obtained from the model, indicating the cost reduction over time for two hypothetical technologies, *Technology A* and *B*. The results highlight the output obtained from the modelling in this work, which enables the identification of conditions in terms of energy efficiency and price developments, and technology learning through capacity deployment and research, that make the different studied technologies cost-competitive in the future. In this example, *Technology A* is subject to higher cost reductions than *Technology B* due to higher learning rate through capacity deployment and more rapid efficiency improvements. Furthermore, the analysis highlights the dominant cost terms for each technology and how their relative impact will evolve for the conditions tested. In this way, the analysis will be able to pinpoint not only how much technological maturation can reduce costs but also what are the key areas for cost reduction.

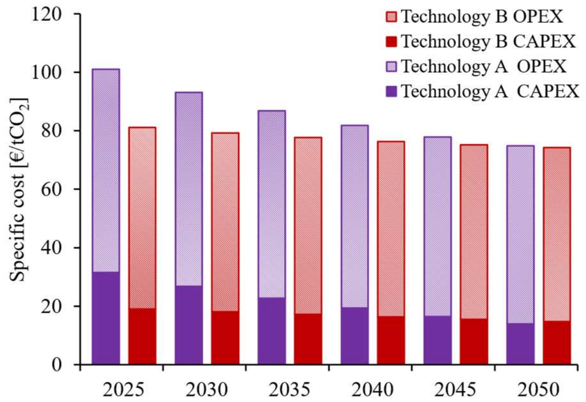


*Figure 1. Exemplifying results showing achieved cost reductions over time calculated for two hypothetical mitigation technologies using the model developed in this work. In this example, Technology A is subject to a higher learning rate and efficiency improvements.*

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*Keywords:* CCS; Innovative technologies; Techno-economic analysis;

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