This work presents best practices and recent advances in cost engineering of CO$_2$ capture, transport and storage technologies.

Cost engineering is an important aspect of the performance analysis of CCS technology. Although many textbooks and scientific publications exist on the ex-ante costing of (emerging) CCS technologies, there is still room to improve costing studies, e.g. because best practices may be unknown to the general audience. Also, as the research field is advancing, new insights and methodological practices emerge. This contribution addresses both. It provides an overview of best practices in cost engineering of CCS technology, and of advances made in the last five years of scientific research.

This contribution will first highlight the importance of using earlier published best practices. They include:

- Getting the process engineering right: capital costing includes equipment sizing, which is not always done up to standards. The resulting cost estimates may be inherently off [1]. This also includes using the right safety margins for equipment design, e.g. to facilitate temperature and pressure excursions.
- Using an established benchmark (e.g. IEAGHG [2], NETL [3], EBTF [4]).
- Using an established CAPEX and OPEX framework, e.g. the white paper by Rubin et al. [5].
- Being transparent on the data use and assumption (cost factor, process and project contingencies, cost plant location, project valuation data, cost year, etc. [5])

Furthermore, it will highlight best practices that have been less discussed but are equally important, among which:

- Using the right cost index. As a rule of thumb, the US CEPCI is used, also for costing of plants in parts of the world other than the US. In reality, costing indices may differ between countries (see Figure 1 as an example). Using local cost indices will provide results that are more reliable.
- Including location differences (location factors). There is a significant difference in construction costs at various locations in the world, 10-30% differences are not uncommon, and sometimes larger differences are reported. A useful source to retrieve location factors is Richardson international construction factors [6].
- Including sound quantitative uncertainty analysis, including validation where possible, and sensitivity analysis. This item also includes stating the appropriate accuracy range of the
capital cost estimate. The accuracy ranges provided by the association for the advancement of cost engineering are a good reference for this [7].

- Process and project contingencies considered for cost evaluation preferably follow the EPRI guidelines to account respectively for performance uncertainties associated with the development status of a technology, and the class of the cost estimate. These guidelines are rarely followed in literature, leading to a structural underrepresentation of costs. For example, assessments of new solvent technologies often assume the process contingencies of commercial solvent processes, independently of the level of maturity of the solvent and application considered.

- Using valid costs for CO₂ transport. This requires selecting a specific CO₂ capture point and storage site, including a transport modality that fits the transport volume and distance (onshore vs. offshore, trunk line vs. point-to-point, ship vs. pipe). Recent studies have shown that transport costs can be significantly higher than the 10 €/tonne that IEAGHG assumes, or the 2 $/tonne that NETL assumes (see e.g. [8], [9]).

Recent advances:

- Hybrid/indirect capital costing method vs. direct costing method (see [10]). The novelty of the hybrid method is that it goes via the first-of-a-kind costs to Nth-of-a-kind costs. First, the EPC costs are escalated using project and process contingencies to reach the FOAK costs. Thereafter the found FOAK TPC is reduced using learning rates to get to an NOAK TPC. Further escalation to TCR can be done if required.

- Economic evaluation assuming flexible dispatch of the power with CCS plant. Power plants are typically dispatched flexibly, and will operate flexibly in the future. Approaches to incorporate flexible dispatch have been published in the last half decade:
  - Imperial college London (e.g. [12], [13]) uses simulated future dispatch profiles including reduced order models of the technical performance and produces total power system costs.

![Figure 1. Comparison of cost indices from the US (CEPCI), the Netherlands (Webci), Germany, and the European Harmonised index of consumer prices (HICP).](image-url)
Utrecht University [14] introduced a techno-economic method that calculates the steady-state techno-economic performance of a power plant with CCS at 5-7 discrete operating points, and aggregate the results to weighted average techno-economic indicators using realistic dispatch profiles.

- Pedigree method to complement quantitative uncertainty analysis, including diagnostic diagrams [1].
- New insights into capture plant integration costs (e.g. ducting) which can significantly increase the costs of retrofitting existing power and/or industrial plants. Examples are included from e.g. the RECAP project [15].
- New insights into the cost of steam production for sorbent regeneration. The cost of steam can vary significantly from case to case, depending on the availability of waste heat, and the existence of a CHP on the premises. Depending on the assumption, the cost of CO2 capture can vary significantly from one case to the other, as well as favour certain technology [16].
- New insights into the cost of CO2 storage and the benefits of CO2 EOR. Recent studies have shown that the cost of CO2 storage may be widely underestimated, especially well costs [17]. When considering CCS with CO2 EOR, most consider that the all the oil revenues resulting of the CO2 injection can be fully considered as a revenue to offset the cost of CCS. However, this is more complex in practice, as alternative EOR technologies can be considered to produce at least some of the oil resulting from CO2 EOR [18]. Furthermore, it is also important to consider that CO2 EOR is often handled by another actor than the CCS chain, and that this can result in a lower agreed face value on the CO2 brought to the EOR storage due to asymmetry in information between actors of the CCS-EOR chain. For these reasons, the potential of CO2 EOR as a market maker for CCS may be overestimated.

References
[12] N. Mac Dowell and I. Staffell, “The role of flexible CCS in the UK’s future energy system,”


