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Short-Cut Correlations for CO_2 Capture Technologies in Small-Scale Applications

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ABSTRACT

The escalating urgency to address climate change has driven carbon capture (CC) technologies into the spotlight, particularly for large-scale emitters, which benefit from economies of scale. However, small-scale emitters account for a significant share of CO_2 emissions, yet such applications remain largely overlooked in the literature. While CC cost is often used as a key performance indicator (KPI) for CC technologies, the lack of standardized cost estimation methods leads to inconsistencies, complicating comparisons, and hindering the deployment of CC systems. This study addresses these challenges by developing flexible short-cut correlations for selected CC technologies, providing estimates of the total equipment cost (TEC) and energy consumption specific to small-scale applications across various CO_2 inlet concentrations (mol%) and capture scales (10 – 100 kt/y). The flexibility of the correlations enables the integration of various cost estimation methods available in the literature and case-specific assumptions (e.g., utility prices), enhancing their consistency and applicability across various scenarios. This approach provides decision-makers with a practical yet simple method for assessing the technical and economic viability of CC systems without conducting extensive simulations or detailed techno-economic assessments (TEAs). Ultimately, this work aims to improve the accessibility of CC technologies for small-scale industries, facilitating their broader application and contributing to the overall goal of reducing greenhouse gas emissions across various sectors.

Keywords: Carbon Capture, Technoeconomic Analysis, Short-cut correlations, Small-scale capture

1. INTRODUCTION

Carbon capture (CC) is crucial for achieving net-zero emissions and mitigating climate change. Despite its critical importance, the current deployment of CC technologies remains insufficient to meet the climate target, indicating an urgency to increase the number of CC applications [1]. Emission sources vary significantly in capture scale, with large-scale emitters benefiting from economies of scale, while smaller-scale applications are often neglected. However, to reach net-zero emissions, CC applications at various emission levels are necessary [2].

While many studies on CC technologies highlight capture cost as a key performance indicator (KPI), there is currently no standardized method in the literature to estimate the cost of CC [3, 4], leading to inconsistencies and incomparable results. This makes it challenging for decision-makers to fairly compare and identify suitable CC options based on the literature results, holding back the deployment of CC units. In addition, conducting detailed simulations and Techno-Economic Assessments (TEAs) to identify viable capture options across various scenarios can be time-consuming and requires significant effort.

To address the aforementioned challenges, this work develops short-cut correlations describing the total equipment cost (TEC) and energy consumption of selected CC technologies for small-capture scale applications. This will allow exploration of the role of CC in small-scale industries and offer a practical means of evaluating the technical and economic viability of various CC systems. Heat integration is not considered due to case-specific waste heat availability.

The goal of this paper is to provide an efficient approach for decision-makers to estimate the cost of CC without the need for extensive simulations and detailed TEAs while ensuring consistent assumptions and cost estimation methods are applied across comparison studies. Also, the correlations are flexible, allowing for various cost estimation methods and case-specific assumptions to fine-tune the analyses for various scenarios.

2. MODELLING

In this paper, Aspen Plus models were developed to study chemical absorption and membrane separation processes which are among the promising CC technologies available today for small-scale applications [2]. The system boundary includes capturing units and CO_2 compressions as presented in Figure 1. Data related to pre-treatment, transportation, and sequestration or utilization are excluded from the current study.

While CO_2-containing gases often include impurities like NO_x and SO_x, it is assumed that the inlet feed gas is free from these impurities. The flue gas temperature is maintained at 170°C to avoid condensation of acid gases. Typically, flue gases contain between 5.5% and 15% H_2O [5] and this study uses a default value of 11% H_2O. The common range for O_2 content is 2-8%, and this study adopts a value of 6.4%, with the remainder of the feed gas assumed to be N_2. A capture rate of 90% was attained across various CO_2 concentrations (5–70 mol%) and feed gas flow rates (corresponding to capture scales between 10 and 100 kt/y), with the minimum purity of the CO_2 product stream established at 95% or higher. Heat integration is not covered in this study due to the availability and characteristics of waste heat is highly case-specific. However, one of the outcomes of this research is to evaluate energy needs, which could be beneficial for future heat integration studies. The captured CO_2 is compressed to 150 bar for transportation through a multi-stage compression system (3 compressors plus a pump) equipped with intercoolers [6].

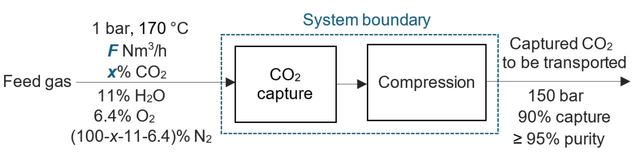

Figure 1. System boundary for CO_2 capture technologies

2.1 Chemical absorption process

Monoethanolamine (MEA) process is one of the widely studied capture technologies where lean solvent (30 wt.% in water) selectively absorbs CO_2 from flue gases and is then sent to the stripper for regeneration (100-140°C at 1 atm). In Aspen Plus, the electrolyte-NRTL thermodynamic package, in conjunction with the ideal gas law, is employed, and the design of the absorber is executed first using equilibrium calculations, subsequently changed to rate-based calculations to accurately model both equilibrium and kinetic reactions occurring within the absorber. A design specification was used to attain a 90% capture rate by adjusting the necessary reboiler duty in the stripper. For the compression loop, the Peng Robinson property package was used. This study employs vendor estimates from the paper of Nwaoha et al. for equipment cost estimation [7]. Other process parameters and cost data as well as detailed validations are presented in the work of current authors [8].

2.2 PolyActive membrane

Membrane CC represents a beneficial alternative technology compared to conventional solvent methods. A membrane separates gas mixture based on varying permeation rates. Membrane separation operates on partial pressure principles and is most effective with high-pressure gas streams [9]. Current advancements indicate that polymeric membranes dominate commercial membrane CC applications and the PolyActive membrane is selected in this study. This paper adopts a two-stage membrane system [9] to achieve enhanced capture rate and product stream purity.

Aspen Custom Modeller (ACM) was used to create a cross-flow membrane module, which was integrated into Aspen Plus as a block component. The process was assumed to be isothermal with negligible pressure drop, ideal gas behavior, and constant permeabilities. The module was divided into 100 cells, where feed conditions were set at the first cell inlet. The retentate ($F_{Ret,k}$) serves as the feed for the subsequent cell, while the permeate ($F_{perm,k}$) is combined with other streams and exits through the last cell. Mass balance calculations are conducted for each cell to determine the permeate flow rate and compositions as described in Equations 1 and 2.

$$F_{Ret,k-1} = F_{Ret,k} + F_{perm,k} \tag{1}$$

$$F_{Ret,k-1} \cdot ZRet_{comp,k-1} = F_{Ret,k} \cdot ZRet_{comp,k} + F_{perm,k} \cdot Zperm_{comp,k} \tag{2}$$

where $ZRet_{comp,k}$ and $Zperm_{comp,k}$ are the molar fractions of each component in each cell for retentate and permeate streams respectively. The permeances [$Nm^3m^{-2}h^{-1}bar^{-1}$] of the PolyActive membrane as well as other process and economic parameters are summarized in the supporting document, Tables S1–S2.

3. METHODOLOGY FOR CORRELATION DEVELOPMENT

This study aims to evaluate the performance of selected CC technologies, specifically MEA and the Polymeric membrane systems, under varying CO_2 concentrations (x_{co_2}, mol%) and flow rates (F, Nm^3/h). To overcome the limitations of literature-based cost comparisons which are often fixed at specific flue gas characteristics and a selected CapEx/ OpEx estimation method, a flexible correlation is developed [8]. The correlation format of Equation 3 was adopted from the work of Hasan et al. [5] and various CapEx estimation methods can be applied to the TEC (total equipment cost) obtained from this correlation. A summary of the CapEx/ OpEx estimation method applied throughout this study is presented in Table S3, in the supporting document.

$$\text{TEC [M€]} = \alpha + (\beta \cdot x_{co_2}{}^{n} + \gamma) \cdot F^{m} \quad (3)$$

$$\text{Energy requirement} = \alpha \cdot e^{n x_{co_2}} + \beta \cdot e^{m x_{co_2}} \quad (4)$$

Where α, β, γ, n and m are fitting parameters and to develop these parameters, several steps were followed: (1) a validated Aspen Plus model [8] was assessed across various CO_2 concentrations and feed gas flow rates generated from the Latin Hypercube Sampling (LHS) at a 90% capture rate; (2) these data points were connected to an Excel-based cost model to evaluate the TEC and specific energy consumptions; (3) results from the Excel model were imported to Matlab for multivariable regressions. The data points used in the correlation development can be found in the supporting document (Tables S4 and S5). The specific energy consumptions were found to be independent of capture scales [8], leading to a correlation format (Equation 4) based on the CO_2 inlet concentration only.

4. RESULTS AND DISCUSSION

4.1 Correlations for CC processes

The developed correlation parameters are presented in Table 1. These correlation results can be used to estimate capture costs relative to CO_2 concentrations and flue gas flow rates within defined ranges. The rule of six-tenths can be utilized for the TEC estimations beyond these boundaries.

In the PolyActive systems, the total membrane area showed a linear correlation with fixed CO_2 inlet concentration. To minimize inconsistencies in cost scaling, the specific membrane cost [$€_{2023}$/t] is separated from other membrane TEC. Therefore, the TEC correlation parameters in Table 1 solely reflect the aggregate process equipment costs, without the total membrane cost. A separate correlation was developed for the membrane cost [€/t] as a function of CO_2 inlet concentration, following a power law due to economies of scale.

$$\text{TEC}_{PolyActive} \left[\frac{€}{\text{t}}\right] = 2.6726 \left(x_{co_2}\right)^{-1.298} \quad (5)$$

4.2 Correlations for CO_2 compressions

The specific TEC of the compression loop depends on the capture scale (S, in t/h) as the flue gas CO_2 concentration does not affect the CO_2 product stream. Equations 6 and 7 present the developed correlations for each CC technology.

$$\text{TEC}_{Comp,\ MEA} \left[\frac{\text{M€}}{\text{t/h}}\right] = 0.3957\,(S)^{-0.602} \quad (6)$$

$$\text{TEC}_{Comp,\ PolyActive} \left[\frac{\text{M€}}{\text{t/h}}\right] = 0.4634\,(S)^{-0.642} \quad (7)$$

Also, the electrical and cooling duties of the compression loop for MEA and PolyActive membrane are presented in Table 2 below. For MEA, the purity of the product stream stayed ≥ 99% and therefore, the specific energy consumptions across the CO_2 inlet concentrations and capture scale remained constant.

Table 2: Energy consumptions of the compression loops

Compression Loop for:	Electrical duty [kWh/t]	Cooling duty [GJ/t]
MEA	87.56	0.594
PolyActive	106.53[*]	0.613[*]

[*] The table lists average energy consumption for the PolyActive membranes at ≥ 95% purity.

Table 1: Correlation parameters for estimating the performances of small-scale CO_2 capture (10-100 kt/y)

Process	α	β	γ	n	m	x_{co_2} [mol%]	F [1000 Nm³/h]
				TEC [$M€_{2023}$]			
MEA	1.0160	1.3364	-0.0123	0.4486	0.7022	$5 \le x_{co_2} \le 50$	$1.30 \le F \le 128.80$
PolyActive	5.3843	0.0071	0.8840	-0.8785	0.4915	$5 \le x_{co_2} \le 70$	$0.92 \le F \le 128.80$
				Specific Cooling Duty $\left[\frac{GJ}{t_{co2}}\right]$			
MEA	9.0860	2.8623	—	-31.5148	0.2572	$5 \le x_{co_2} \le 50$	$1.30 \le F \le 128.80$
PolyActive	21.1248	3.3077	—	-22.9241	-1.9204	$5 \le x_{co_2} \le 70$	$0.92 \le F \le 128.80$
				Specific Reboiler Duty $\left[\frac{GJ}{t_{co2}}\right]$			
MEA	1.6315	3.5678	—	-38.4307	-0.0199	$5 \le x_{co_2} \le 50$	$1.30 \le F \le 128.80$
				Specific Electrical Duty $\left[\frac{kWh}{t_{co2}}\right]$			
MEA	9.4061	2.2475	—	-21.6650	-1.2483	$5 \le x_{co_2} \le 50$	$1.30 \le F \le 128.80$
PolyActive	1227.2	263.27	—	-18.9830	-0.9304	$5 \le x_{co_2} \le 70$	$0.92 \le F \le 128.80$

In this work, average values are presented in Table 2 when the purity is ≥ 95% as a simplified approach to estimate the energy consumption.

4.3 Correlations and relative errors

The relative errors between the correlation results and the data points obtained from detailed TEAs for the selected CC technologies are presented in Table 3.

Table 3: Relative errors of the capture technologies

MEA	Average relative error [%]	Min/ Max relative error [%]	R^2
TEC	4.28	0.014/ 8.50	0.975
Reboiler duty	0.12	0.002/ 0.40	0.996
Electrical duty	2.87	0.03/ 8.59	0.997
Cooling duty	1.38	0.19/ 7.54	0.997
PolyActive			
TEC	1.90	0.004/ 4.92	0.999
Electrical duty	2.57	0.42/ 8.77	0.999
Cooling duty	3.95	0.24/ 8.67	0.999

Given the scarcity of real CC project data for small-scale applications in the public domain, it is important to clarify that these errors do not represent the uncertainty of a real CC unit but rather deviations between the correlation and TEA data used in this study. For CapEx/ OpEx, uncertainties as high as 10 to 20% are common during a process scale-up [5] and therefore, the average error as well as the maximum errors depicted in the correlations can be considered within the expected variations. Correlation development is iterative and more data points can be added to improve the correlation results. The validity of the developed correlations is demonstrated through the case studies.

4.2 Case study

4.2.1 Cement industry CC (20.5 mol%, 111 kt/y)

In this section, correlations from this study are applied to case studies presented by IEAGHG [2], starting with a small-scale cement plant. The CapEx estimation method used in the case study is presented in the supporting document. Key assumptions and input data are presented in Table 4. Note that natural gas is used to generate steam required by the MEA process while for the PolyActive membrane, no steam is required. Detailed breakdowns of the MEA capture cost retrieved from IEAGHG [2] as well as the correlation results for the MEA and PolyActive membranes are presented in Figure 2. CapEx is one of the dominant factors and accounts for close to 50% of the capture cost for small-scale application. Comparing the MEA correlation CapEx to the literature value, a difference of 6% was observed while the NG fuel costs showed a deviation of 5%. In the case of electricity costs, the report extracted electrical energy consumption from a coal-fired power plant case study treating a flue gas at 4.1 mol% CO_2 concentration without conducting a detailed simulation. As indicated in Table 8, the flue gas considered in this case study has a high

Table 4: Case study process/ economic inputs and assumptions [2] for the small-scale cement plant

Parameters	**Values**	**Parameters**	**Values**
CO_2 concentration	20.5 mol%	Operating hours	7451 h/y
Capture scale	111.3 kt/y	CEPCI (2024 April)	799.5
Process lifetime	25 y	Electricity	132.31 $/MWh
Discount rate	10%	Natural gas (NG) price	22.82 $/MWh

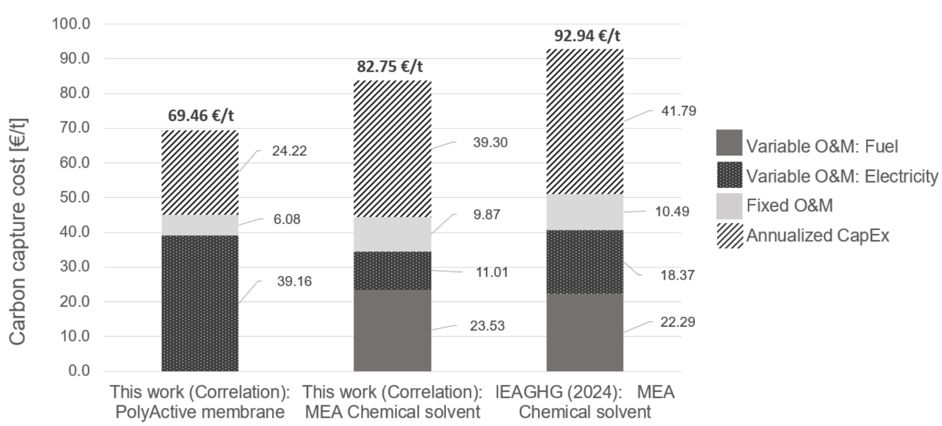

Figure 2. Detailed breakdown of carbon capture and compression cost [€/t]: Case study 1

concentration of 20.5 mol%. At low CO_2 concentrations (e.g., 4.1 mol%), high flue gas volumes will pass through a blower and more power will be required. Also, the study reported 1.58 MW_{el} for the compression of CO_2 product which is higher than the power consumption considered in this study (1.11 MW_{el}), but no details about product compression was given. In addition, higher solvent pump power consumptions were considered in the literature by accounting for pressure drop in pipelines (a pump head of 10 bar) which was not considered in this study. These differences in the assumptions lead to a deviation of 45% in electricity costs. Overall, the MEA correlation showed a capture cost of 82.75 €/t with a difference of 11% compared to the reported value which is within the expected deviation defined by AACE [10]. Assuming more accurate power consumptions were applied in the literature result, the difference in capture costs for MEA process could be even lower which shows a good applicability of the correlations.

The capture cost obtained using the PolyActive correlations was found to be 69.46 €/t which is lower than the MEA process. This is possible since the membrane process can be less CapEx intensive and more cost-effective at high CO_2 concentrations. Also, membranes are well-suited for small-scale applications due to their modularity. However, 56.3% of the capture cost arises from the electricity cost and therefore, sources of electricity will be an important criterion to be considered.

4.2.2 Energy from Waste (EfW) (10 mol%, 90 kt/y)

An EfW plant with a capture scale of 90 kt/y was considered in the second case study where process parameters and assumptions are outlined in Table 5. The EfW plant without a CC unit produces 7.7 MW_{el} and 8.1 MW_{th}. Note that NG cost is not considered since all the steam needed for solvent regeneration is assumed to be supplied by the steam turbine from the EfW plant. Based on this, a steam turbine loss of 3.89 MW_{el} was assumed in the literature [2] and applied in the correlation results as well. Since the EfW plant produces electricity, a wholesale electricity price of 56.85 $/MWh was retrieved from the literature [2] and applied in this case study. The detailed breakdowns of capture costs are shown in Figure 3.

As observed in the first case study, the CapEx is the main contributor to the capture costs (54% for the literature MEA results and 59% for the MEA correlation result). For the annualized CapEx, a difference of 12% was observed between the correlations and the literature, while for the electricity cost, a difference of 22% was observed. As explained in Section 4.2.1, much higher power consumption for the compression loop and the solvent pumps are used in the literature [2]. Overall, a capture cost of 82.92 €/t was obtained from the MEA correlations with a difference of 3.54% compared to the literature value of 79.98 €/t. In the case of the PolyActive membrane, a capture cost of 71.48 €/t was obtained using the correlations with the same assumptions, which is a cheaper CC option than the conventional MEA CC in the EfW case as well.

Table 5: Case study process/ economic inputs and assumptions [2] for EfW process

Parameters	Values	Parameters	Values
CO_2 concentration	10.0 mol%	Operating hours	7451 h/y
Capture scale	90.0 kt/y	CEPCI (2024 April)	799.5
Process lifetime	25 y	Electricity	56.8 $/MWh
Discount rate	10%	Natural gas (NG) price	NA

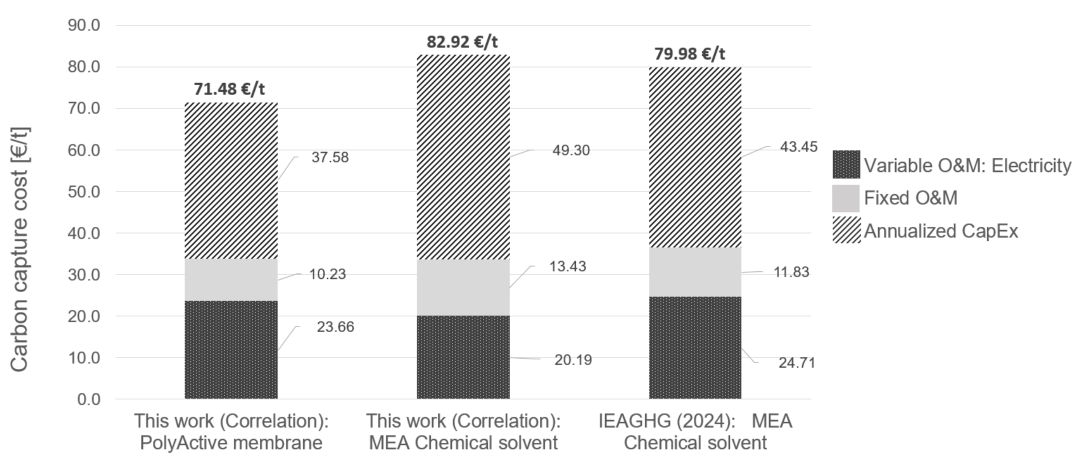

Figure 3. Detailed breakdown of carbon capture and compression cost [€/t]: Case study 2

CONCLUSION AND PERSPECTIVES

In this paper, small-scale correlations for the MEA and the PolyActive membrane CC technologies are developed and the applicability is demonstrated in the case studies. These correlations can be applied across various CO_2 inlet concentrations (between 5 and up to 70 mol%) and capture scales (10-100 kt/y). Also, a consistent CapEx/ OpEx estimation method can be applied throughout the comparison studies to minimize discrepancies. More importantly, case-specific utility costs can be applied to the correlation results to fine-tune the capture costs depending on the considered case studies. As a benchmark CC process, MEA correlations are presented in this work which is one of the well-suited CC options for large-scale applications. However, small-scale CC processes are CapEx intensive due to the absence of economies of scale, leading to higher costs per ton of CO_2 captured. Therefore, technologies with a lower CapEx intensity (e.g., membranes) will have higher potential for small-scale emitters. Also, modularity and installation area of technologies will be crucial KPIs for small-scale applications due to often limited space availabilities. In the perspectives, new emerging technologies such as advanced chemical absorption or cryogenic CC can be studied to enrich small-scale CC applications in the literature.

Overall, these easy-to-use small-scale correlations are envisioned to assist with decision-making processes for small-scale CC and improve deployment of CC units by providing a framework to fairly compare various CC technologies.

DIGITAL SUPPLEMENTARY MATERIAL

The supplementary materials can be found at: https://psecommunity.org/LAPSE:2025.0031

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