TECHNO-ECONOMIC ASSESSMENT OF CO_2 COMPRESSION FOR CCUS PROJECTS IN BRAZIL

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Abstract. *This paper presents a comprehensive techno-economic analysis of carbon dioxide (CO_2) compression as part of the carbon, capture, utilization, and storage (CCUS) value chain processes with a specific focus on future ventures in Brazil. The method includes equipment specification and detailed cost estimation models for compressors and related infrastructure, aiming at providing valuable insights into performance and economic feasibility of a capture/transportation system. Key technical and economic parameters are evaluated, such as energy consumption during the compression stages, capital investment requirements, and operating and maintenance (O&M) costs of the system. As a seminal contribution nationwide, this study offers a new perspective for the hard-to-abate Brazilian industry interested to promoting sustainable development and achieving their carbon mitigation goals through CCUS initiatives.*

Keywords: *Decarbonization, CO_2 compression, energy transition, heavy industry.*

1. INTRODUCTION

Several nations are committed to reducing their carbon footprint and looking for economically viable ways to reduce their CO_2 emissions. Electrification-based technologies, for instance, are a clear example of energy transition. However, the challenges for decarbonizing some heavy industry segments (so-called *hard-to-abate sectors*) require large-scale alternatives.

In this scenario, carbon capture, utilization and storage (CCUS) technologies emerge as strategic solutions towards carbon neutrality. When advocating for the repurposing of existing industrial infrastructures, CCUS reduces implementation costs and enables carbon dioxide capture from emission sources, such as industrial chimneys (or flue), or even directly from the atmosphere. Finally, it can drive the emissions for reuse or permanent storage into underground geological reservoirs.

Given the geological storage reservoirs located mainly in the coast and all effort applied by the industry and their high qualified workforce, Brazil has a great potential to become a regional and global hub for CCS. In the year of 2023, 13 $MtCO_2$ was injected at pre-salt Santos Basin reservoirs (Global CCS Institute, 2024).

In addition, Petrobras is studying the implementation of an unprecedented CO_2 capture and geological storage hub project in Brazil in partnership with other companies. According to Petrobras (2023), the inedited project of capture hub in Brazil, consists of implementation an complete infrastructure to transport CO_2 from capture sites (hubs in industrial facilities) to its permanent geological storage in reservoirs below the seabed. Located on Cabiúnas (north of Rio de Janeiro), this first pilot plant expected storage of 100 thousand tonnes of CO_2 per year (0.1 Mtpa) and cover all stages of the process - capture, transport, utilization/geological storage and monitoring (ANP, 2024a,b).

Despite the strong adequacy for deploying carbon sequestration in the country, its continental territory and sparse location of industry plants encourages equal effort towards carbon capture and utilization (CCU). CCU-techs convert CO_2 into valuable products and create new sustainable economic chains, especially in those regions located far from high-prospectivity storage sites. Besides adding up to the storage model, CCU-techs can consolidate the Brazilian protagonism as a low-carbon economy while creating innovation, regional integration, and value.

In this context, the technical-economic assessment of CCUS projects becomes essential for decision-making. The costs involved in the implementation, operation and maintenance of CO_2 capture, compression, transportation, utilization or storage vary widely depending on the technology used, the scale of the project, and its geographic location. Cost-benefit analyses, feasibility studies and multi-criteria models should be incorporated since the initial planning stages in order to guide efficient investments, reduce financial risks, and ensure the competitiveness of proposals, especially in developing countries like Brazil.

This study focuses on the carbon dioxide compression phase following capture and separation, preparing the gas for transport via pipelines. A key objective is to accurately estimate the costs associated with the pre-pipeline compression stage. This calculation is important not only for evaluating the feasibility of a project, but also grounding discussions on the economic potential of CCU and storage applications. By understanding these costs, stakeholders can better assess how to implement hubs across the country, reduce logistics costs, and unlock new business opportunities.

2. PIPELINE-ENTRY CO_2 COMPRESSION COST MODEL

This section presents the model to estimate the operating and infrastructure costs for the compression of carbon dioxide at the pipeline-entry phase, which lies between the post-capture and pre-transportation stages under engineering requirements. The cost modeling follows McCollum and Ogden (2006), as well as a compilation of reports and technical manuals relating equipments and operational conditions (Ebara, 2016; ITT, 2023; Siemens, 2009, 2024; Usher, 2011). We underscore that the assumptions for this study were based on a specific compression infrastructure model. It should be pointed out that alternative configurations may require a different modeling.

2.1 CO_2e conversion

Companies generally present their emission balance sheets in annual reports with values expressed in units of carbon dioxide equivalents (CO_2e), usually in Mtpa (million tonnes per annum). It is important to understand the conversion procedure behind this unit in order to know the precise total amount of gas that could be captured at a given industrial plant and quantify the real abatement share from the registered inventory.

The general formula for the CO_2e unit as a function of the emitted gases is given by

$$CO_2e = \sum_{i=1}^{n} m_i \, GWP_i, \tag{1}$$

where m_i and GWP_i are, respectively, the mass and the global warming potential of the $i-$th greenhouse gas in relation to CO_2 in a horizon of 100 years according to IPCC (2024) and n is the number of emitted gases. This means that, each industrial source (cement, steel, iron and steel etc.), will have a different compound in determining the equivalence.

The efficiency of a CO_2 capture plant can vary significantly according to the technological arrangement adopted. Typical capture operations presents an efficiency of 90% from the feed stream with a growing trend to reach 95% applying new technologies at the process (Global CCS Institute, 2025).

2.2 Compression and pumping power requirement calculation

The study considers that, at the pipeline-entry phase, the carbon dioxide will be compressed from the atmospheric pressure (or inlet pressure), P_i = 0.1 MPa, to the critical phase pressure, P_{co} = 7.38 MPa. After reaching the critical phase pressure, also called the dense phase, one assumes that the fluid can be compressed up to the final pumping pressure, P_f = 15 MPa, as depicted in Fig. 1. These settings are widely applied in the literature (McCollum and Ogden, 2006) and favor reduced compression costs as elucidated next.

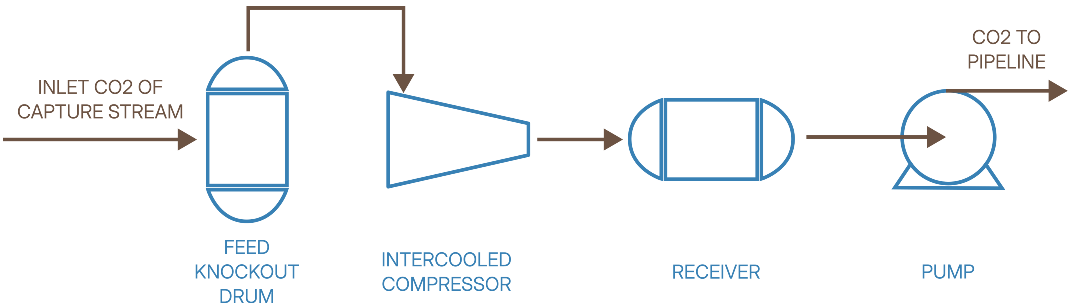

Figure 1. Simplified diagram of the compression process. Source: adapted from (Usher, 2011).

First, we calculated the compression ratio, CR, through the formula

$$CR = \sqrt[N_s]{\frac{P_{co}}{P_i}}, \tag{2}$$

where N_s is the number of stages. This study has assumed a 4-stage Integrally Geared Compressor (IGC). This technology allows for optimized impeller design for each compression stage, thus improving efficiency (Usher, 2011). The system also allows for integrated installation with coolers (intercoolers).

Second, we calculated the stage compression power for the s-th stage, W_s, according to the following equation:

$$W_s = \left(\frac{1}{24}\right)\left(\frac{1000}{3600}\right)\left(\frac{\dot{m} Z_s R T_{in}}{M \eta_{is}}\right)\left(\frac{k_s}{k_s - 1}\right)\left(CR^{\left(\frac{k_s - 1}{k_s}\right)} - 1\right), \tag{3}$$

where $\dot{m}$ is the CO_2 mass flow rate to be transported to the storage site in tonnes per day, R = 8.314 J mol^{-1} K is the ideal gas constant, T_{in} = 315.15 K is the temperature at the compressor inlet, M = 44.01 kg kmol^{-1} is the molecular weight of CO_2, η_{is} = 0.82 is the isentropic efficiency of compressor – assumed here to be 82%, since it varies between 80% and 85%, Z is the CO_2 compressibility and $k = (C_P/C_V)$ is the average ratio of specific heat of CO_2, varying per stage (Table 1). Lastly, the preceding fractions are conversion factors into tonne per second units.

Table 1. Compression parameters per stage.

	Stage 1	Stage 2	Stage 3	Stage 4
Pressure range [MPa]	0.1 - 0.29	0.29 - 0.86	0.86 - 2.52	2.52 - 7.38
Z [ ]	0.995	0.986	0.959	0.875
k [ ]	1.273	1.285	1.321	1.448

This way, the total power required for compression is given by

$$W_C = \sum_{s=1}^{N_s} W_s. \tag{4}$$

The maximum gearbox rating for a single compressor train is $60.000\,\mathrm{kW}$. If the total power required exceeds this threshold, the flow rate should be distributed over additional compressors trains Siemens (2009), whose number can be expressed by Eq. (5).

$$N_t = \frac{W_C}{60,000} \tag{5}$$

Up to this point, the power requirement has been estimated for the compressor stages. The next step involves evaluating the operation of a centrifugal pump. To calculate the pump power requirement, W_P, equations from the study by McCollum and Ogden (2006) are employed. In this context, the suction pressure and the discharge pressure were the same as P_{co} and P_f, respectively. This way, one has:

$$W_P = \left(\frac{1000}{24}\right)\left(\frac{10}{36}\right)\left[\frac{\dot{m}(P_f - P_{co})}{\rho\,\eta_p}\right], \tag{6}$$

where $\rho = 630\,\mathrm{kg\,m^{-3}}$ is the CO_2 density during the pumping phase, η_p = 0.75 is the pumping efficiency, and 10/36 is the a conversion factor (bar per MPa / m^{3}bar/hour per kW).

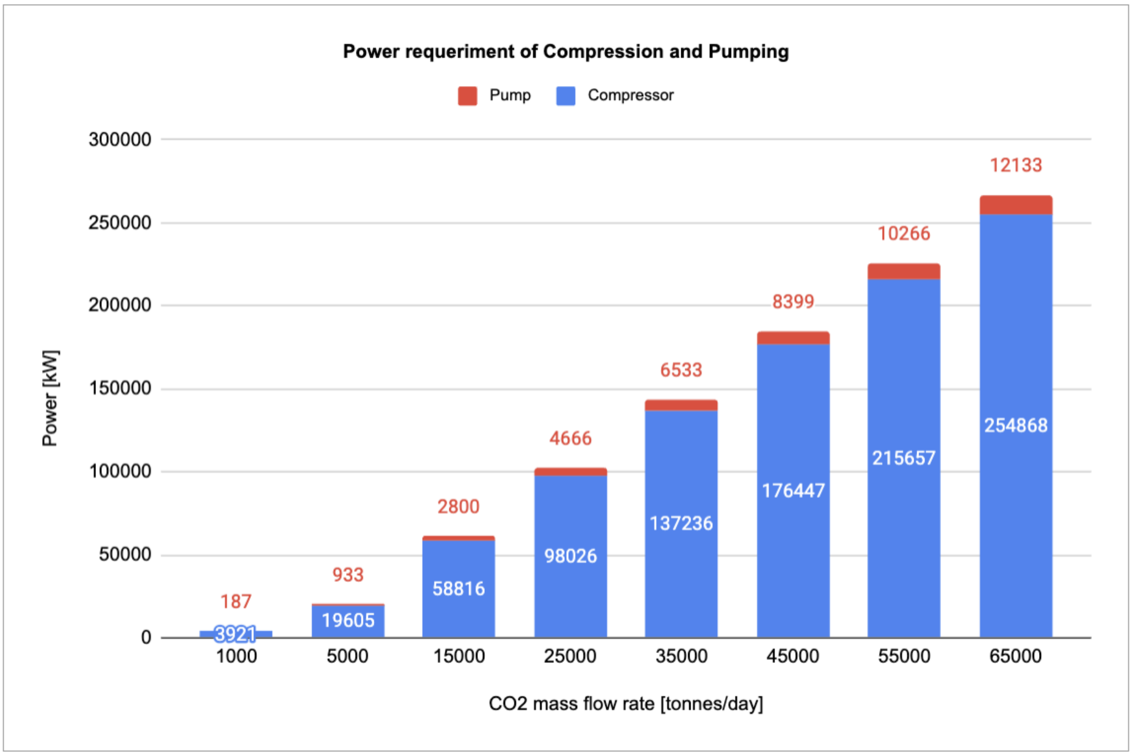

Figure 2. Power requirement for compression and pumping after the capture phase as a function of the CO_2 mass flow rate.

The power requirements for both compression and pumping are presented in Figure 2. As expected, power consumption increases proportionally with the CO_2 mass flow rate, demonstrating a linear relationship for both processes, given that the mass flow rate appears as a direct multiplier in the equations.

Notably, separating the compression phase into two distinct components – compressor and pump – highlights important differences in power demand. While the compressor power requirement rises sharply with increasing flow rate, the pumping power increases at a significantly lower rate. This is primarily due to the pressure difference handled by each stage: the compressor raises the pressure from 0.1 MPa to 7.38 MPa (approximately 74-fold), whereas the pump increases it only from 7.38 MPa to 15 MPa – roughly a twofold increase.

The data show that, although the pumping requirement scales with flow rate, it consistently contributes less than 5% of the total power, independent of the flow rate analyzed. This trend underscores that compression is the dominant factor in energy consumption for CO_2 transport post-capture, making it the critical target for energy optimization efforts in such systems.

2.3 Capital, operational, and maintenance costs calculation

Estimates of capital investment for a project, particularly during the early, pre-design stages, are typically based on limited information or on analogies with similar past projects. As the project advances and more detailed data become available, these estimates can be refined, gradually converging toward more accurate final values. Despite their inherent uncertainty, such early estimates are crucial for assessing initial feasibility, comparing alternative initiatives, and determining whether a project merits continued development (Peters and Timmerhaus, 1991).

This section presents cost estimation procedures following the methodology of McCollum and Ogden (2006), with all values adjusted to reflect 2025 price levels. Relevant cost escalation indices and conversion factors are introduced where appropriate. All monetary values are expressed in US dollars (US$).

The capital costs for compression, C_C, and pumping, C_P, are estimated using the following expressions:

$$C_C = m_t N_t \left\{ \left[0.13 \cdot 10^6 (m_t^{-0.71}) \right] + \left[1.40 \cdot 10^6 (m_t^{-0.60}) ln \left(\frac{P_{co}}{P_i} \right) \right] \right\} \tag{7}$$

and

$$C_P = 1.11 \cdot 10^6 \left(\frac{W_P}{1000} \right) + (0.07 \cdot 10^6) \tag{8}$$

with

$$m_t = \left(\frac{1000}{24} \right) \left(\frac{\dot{m}}{3600 N_t} \right) \tag{9}$$

The N_t factor both in the C_C and m_t equations points out that the cost will not be overpriced in case of lower mass flow rate.

The cost equations provided by McCollum and Ogden (2006) are based on data reflective of the U.S. economic scenario in 2005. Therefore, it is necessary to apply a cost adjustment index to update these values to 2025. To account for inflation and changes in equipment pricing over time, this study employs the *Marshall and Swift Equipment Cost Index*. This widely accepted index allows for the temporal correction of capital cost estimates. The following adjustment equation is adopted from Peters and Timmerhaus (1991):

$$\beta_p = \beta_o \left(\frac{\mu_p}{\mu_o} \right), \tag{10}$$

where β_p is the cost adjusted to the present time, β_o is the original cost, μ_p is the index value corresponding to the present time, and μ_o is the index value at the time the original cost was estimated.

Figure 3 shows the capital cost of compressors and pumps expressed in US$/kW. A pronounced downward trend in specific cost (per unit of power) is observed as the CO_2 flow rate increases. This reflects the effect of economies of scale, which enhance the economic efficiency of systems operating at higher capacities. The data reveal that compressors are more sensitive to scale effects, with a marked decrease in specific cost as capacity increases. In contrast, the cost of pumping experiences an initial decline but quickly stabilizes, remaining relatively constant at higher flow rates.

Slight increases in the compressor cost curve at low values can be attributed to the addition of extra compressor trains once certain power thresholds are exceeded. This modular expansion contributes to local increases in specific cost. Overall, the analysis highlights that the economic feasibility of CO_2 compression systems benefits significantly from large-scale operations, with compressors being the primary beneficiaries of scale-driven cost reductions.

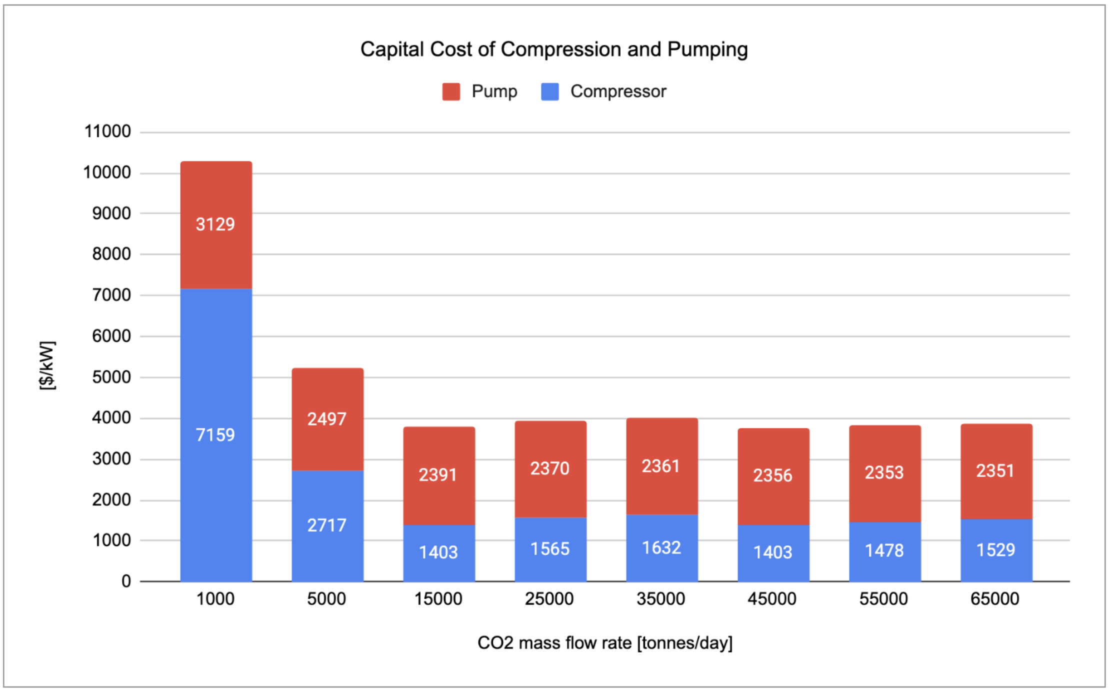

Figure 3. Capital cost of compressor and pump as a function of the CO_2 mass flow rate.

2.4 Total annual compression costs calculation

The total capital cost of compression, C_{TCC}, represents the sum of compression and pumping capital costs:

$$C_{TCC} = C_C + C_P \tag{11}$$

The Capital Recovery Factor (CRF) represents the ratio used to calculate the present value of a series of equal annual payments over the economic lifetime of an asset. It is commonly used to estimate the annualized capital cost of equipment and can be determined using Eq. (12).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{12}$$

where i is the nominal discount rate and n is the project lifetime in years. For CCUS industrial projects, i varies from 7% to 10% and n from 20 - 30 years. This study adopted 8% and 25 years for reference, as well as CRF = 0.0936/year, which updates the annual capital cost (C_y) formula with C_{TCC} as

$$C_y = C_{TCC} \cdot CRF. \tag{13}$$

The International Energy Agency (IEA) suggests a correction factor, ($O\&M_F$) of 0.05 (IEAGHG, 2006). Applying this factor to the Total Capital Cost we can calculate the annual operational and maintenance cost according to Eq. (14).

$$O\&M_y = C_{TCC} \cdot O\&M_F \tag{14}$$

Annual electric power cost of the total compression phase (compressor + pump) can be calculated multiplying the total power requirement by a Capacity Factor (CF) and the price of the electricity (p_e).

According to EIA (2025) the average 2024 price of industrial electricity (p_e) in the US = 8.15 cent/kWh.

The index CF can be found in Peters and Timmerhaus (1991). For compression we should adopt CF = 0.80.

$$E_y = E_{Comp} + E_{Pump} = p_e(W_C + W_P)(CF \cdot 24 \cdot 365) \tag{15}$$

Finally, the Total Annual Compression Cost of CO_2 in pre-pipeline compression phase is

$$Total\ Annual\ Cost = C_y + O\&M_y + E_y \tag{16}$$

Figure 4 presents the breakdown of Total Annual Costs associated with the CO_2 compression phase (including both compressor and pump), highlighting the individual contributions of Annualized Capital Cost (C_y), Operation and Maintenance ($O\&M_y$), and Energy Cost (E_y) as a function of the CO_2 mass flow rate.

Across all project scales, the cost associated with electrical energy consumption emerges as the dominant component of the Total Annual Cost. Even at lower flow rates, the energy cost represents the largest share, followed by capital and O&M costs, which contribute relatively less. As the CO_2 flow rate increases, the energy cost's proportional impact becomes even more pronounced, reflecting its direct dependence on the system's power requirements.

While both capital and O&M costs increase with flow rate, their growth is considerably less steep compared to the energy cost. Operation and maintenance expenses consistently represent a minor portion – typically between 1% and 3% – of the total annual cost. These figures collectively represent the direct annual cost of implementing and operating the compression phase prior to pipeline transport.

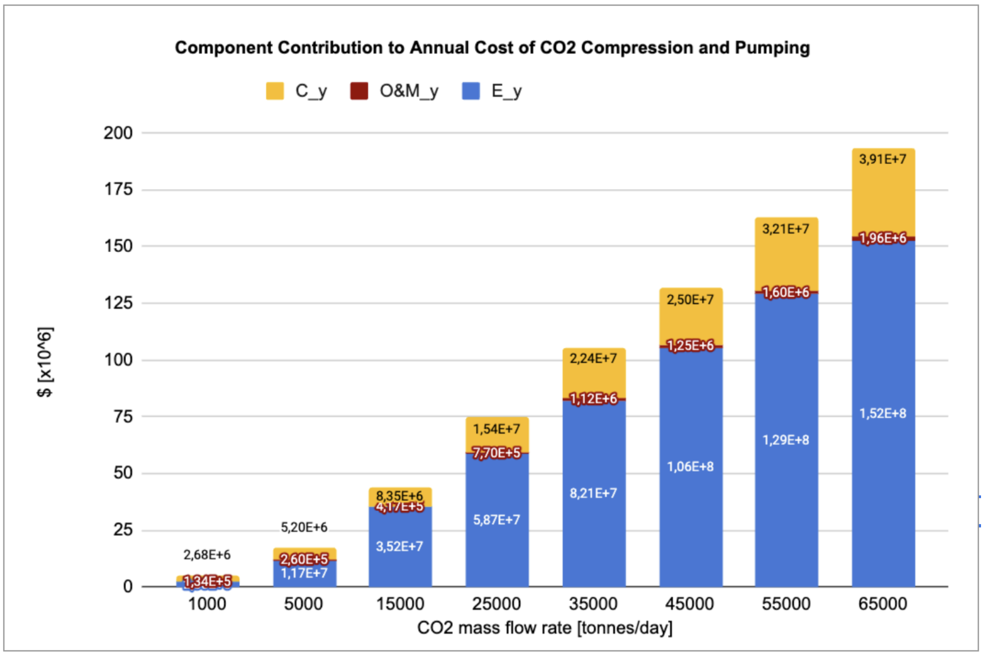

Figure 4. Component Contribution to Annual Cost of CO_2 Compression and Pumping as function of CO_2 mass flow rate

3. COMMENTS AND FINAL CONSIDERATIONS

The objective of this work is not only to present updated cost estimates for pre-pipeline CO_2 compression based on a sequence of engineering formulas, but also to contribute meaningful data to the broader discussion on the need to invest in and foster new technologies for the productive utilization of captured CO_2. While geological storage remains a critical solution for decarbonization, it should not be regarded as the sole or primary destination for captured CO_2, particularly for industries located far from storage sites.

To illustrate this, we analyze two industrial facilities located in the state of São Paulo, Brazil, both of which are participants in the GHG Protocol. Using their 2023 Scope 1 emissions data, we estimate their costs associated solely with pre-pipeline gas compression, based on the methodology developed in this study. One facility from the steel sector reported emissions of approximately 23 Mtpa, while the other, from the cement sector, reported around 15 Mtpa. In both cases, the emitted gases can be considered to contain approximately 98–99% CO_2.

Under these assumptions, the estimated annual cost for gas compression alone would be approximately US$ 165 million and US$ 130 million for the steel and cement plants, respectively. These figures do not include the subsequent costs of transporting the gas to injection wells, which further increases the financial burden. This highlights the importance of exploring alternative markets and applications for captured CO_2, beyond traditional carbon credit mechanisms. Notably, the results emphasize the benefits of developing industrial carbon hubs to increase transport volumes and reduce unit costs through economies of scale. Additionally, it is worth noting that earlier studies from 2005–2006 considered maximum CO_2 flow rates of around 25,000 tonnes per day – demonstrating the considerable growth in industrial carbon capture capacity over the past two decades and reinforcing its growing relevance to both climate strategies and emerging business models.

4. ACKNOWLEDGMENTS

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6. RESPONSIBILITY FOR INFORMATION

The authors are solely responsible for the information included in this work.