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Cost–benefit evaluation of membrane technology for carbon emission reduction in Indonesia

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Abstract

This study investigates the financial viability of membrane technology in mitigating CO_2 emissions in the oil and gas industry in an Indonesian context. A model calculation is presented with the for a sample company (company X) but provide a global perspective regarding membrane technology when considering different scenarios of costs (of carbon capture) and savings (through decreased carbon costs) to reconciling environmental and economic goals. Company X decreased its CO_2 emissions from 34 to 12%, using CO_2 membrane technology on its daily production corresponding to an annual emission reduction of 7,095,666 tons of CO_2. As a result of the carbon reduction, the annual carbon tax decreased significantly from 14,191,333 to 4,943,782 USD yielding annual cost savings of 9,247,551 USD. However, considering the high costs of the technology, and the low Indonesian carbon tax rates in an international context, this investment does not pay back solely from a carbon cost reduction perspective. When considering higher carbon cost scenarios, like in China, the EU and the US (California), that may be the future direction for Indonesia, as well, results indicate that the membrane technology delivers a financial payback already (especially at the carbon price levels of the EU and California). The study discusses the potential future directions in Indonesian carbon pricing and the decrease of membrane technology costs through technological developments, as well as other benefits of the membrane technology.

Keywords Membrane technology, Carbon dioxide emission reduction, Carbon tax, Oil and gas sector, Sustainable practices, Indonesia

1 Introduction and literature review

In recent years, Indonesia's growing international prominence can be attributed to its large and growing population and economy, its extensive rainforest areas and its proactive stance on climate change [1]. The government, in collaboration with the private sector, has taken serious efforts to address the issue of carbon emissions [2]. Indonesia, as one of the largest oil and gas producers in Southeast Asia, committing to a 31.89% emission reduction by 2030 under the Paris Agreement [3]. According to the data reported by the International Energy Agency (IEA) in 2022, the total share of oil in the energy supply of Indonesia was approximately 28.1%, while the share of gas was approximately 12.7% [4, 5]. In 2025, based on Special Task Force for Upstream Oil and Gas Business Activities (SKK Migas) report, the oil production of Indonesia is 579,900 barrels per day and 6,900 standard cubic feet of gas per day (MMSCFD) of gas [6, 7]. The recent escalation in drilling operations and the discovery of new hydrocarbon reserves present a viable solution to meet the country's energy demands, thereby supplementing the ongoing importation of oil and gas. However, Indonesia is currently facing an energy deficit. According to data reported by the Committee on Electronic Information and Communication (CEIC) in 2023, the country's oil consumption stands at approximately 1.6 million barrels per day [8]. This indicates that Indonesia must import approximately 1 million barrels to meet its domestic demand.

All over the world, governments tend to contribute to control the greenhouse gas contributions of their countries, summarized by Nationally Determined Contributions (NDCs) linked to the Paris Agreement [9]. These include economic regulations, associate prices to carbon releases at industries with significant carbon-dioxide emissions [10]. The two major tool, to enforce the 'polluter pays principle' is either issuing a carbon tax (to be paid per unit of output) or creating a market for carbon-dioxide, where large emitters can trade with carbon dioxide emission rights, in order to cover their releases [11]. In the context of carbon pricing, it is imperative to acknowledge its role as a pivotal instrument in the fight against climate change [12]. This is achieved by internalizing the external costs associated with carbon emissions [13]. This mechanism aims to reduce carbon emissions by providing encouragement or incentives to industry players for the carbon emissions they produce [14]. Popular schemes, such as carbon taxes or cap and trade systems, will make high-polluting activities costly and encourage them to transition to sustainable business processes and technologies [11]. On a global scale, over 50% carbon pricing initiatives were implemented in 2021, encompassing approximately 20% of greenhouse gas emissions [12, 15]. This development serves to bolster the appeal of carbon pricing schemes [16]. The implementation of carbon pricing schemes varies by region; some countries have adopted a very comprehensive carbon pricing framework as part of their climate change policies, while others, especially developing countries face significant challenges in implementing and executing them [17]. Empirical evidence has demonstrated that the implementation of carbon pricing schemes leads to a substantial and effective reduction in gas emissions [18]. Green's analysis indicates that the implementation of a carbon tax scheme is more effective in reducing emissions than an emission trading system [19]. Notwithstanding the challenges associated with the implementation costs and the equitable application of carbon pricing policies, these obstacles can be surmounted by the judicious formulation of policies [20]. A salient example is the implementation of a green and social innovation program financed by carbon tax revenues, which has the potential to mitigate the adverse impacts and achieve consensus among all relevant parties [21].

However, to cope with regulation and decrease carbon emissions (otherwise than decreasing their production and thus their contribution to the economy), governments, companies and facilities need innovative technologies [10]. These efforts to strike a balance between economic growth and environmental protection is facilitated by the implementation of carbon emissions membranes, which are designed to enhance the value chain of companies, thereby reducing CO_2 emissions during production processes [22].

In Indonesia, an economy highly depending on the oil and gas industry, there are still many oil and gas companies that have not implemented the membrane technology [23], especially those that produce natural gas [24]. The implementation of the membrane technology depends on many factors, but one key area of success is whether CO_2 gas is separated from the natural gas mixture in a financially beneficial way [25, 26]. Therefore, this study aims to perform a cost–benefit model calculation to explore the business relevance of membrane technologies in handling the CO_2-emissions in the context of the Indonesian oil and gas sector.

The basic idea of the membrane technology is that it captures carbon dioxide, cleans it and transforms it into useful products [27]. Not only does the advanced separation membranes technology enhance company profits with the use of CO_2 gases, but it also reduces emissions [28]. CO_2 membranes technology is one of technologies to capture or separate the CO_2 from raw mix gas with the principle of selective membranes which is the ability to separate specific components from the mix gas based on the chemistry and physic characteristics [29, 30]. In this case, CO_2 is able to penetrate the membrane quickly compared to other gas mixture compounds such as CH_4, N_2 and other gas compounds [29]. Membrane technology holds considerable promise as a means of reducing carbon emissions by selectively extracting CO_2 from industrial and oil and gas fields where it is present as a byproduct [31]. Membrane technology is contingent upon the utilization of advanced materials, including polymers, carbon, ion exchange, and mixed-matrix membranes [32–35]. The mechanisms in action operate via solution-diffusion, molecular sieving, or electrochemical mechanisms [33, 34, 36].

The performance of the membrane is determined by a number of operational parameters, including pressure, temperature, membrane thickness, and selectivity [31]. This technology offers numerous advantages across a variety of domains. Primarily, from an energy and cost-effectiveness perspective, membrane systems frequently demand less energy than conventional thermal or chemical separation processes, particularly in applications such as desalination and gas purification [28, 37]. Secondly, the utilization of polymeric membranes and advanced materials has the potential to further reduce energy requirements in oil refining and fractionation [37]. Thirdly, regarding design and operation, membrane units are characterized by their compact and modular nature, which renders them particularly well-suited for confined spaces, such as those found in offshore locations [28, 38–40]. Additionally, they possess a high degree of flexibility with respect to subsea installation. Fourthly, this technology has the added benefit of minimizing the use of chemical additives, thereby reducing secondary pollution and waste generation [38–40]. Finally, this technology exhibits high separation efficiency and versatility with microfiltration, ultrafiltration, and nanofiltration, effectively removing a wide range of contaminants, including gas emissions [38].

The diagram below describes oil and gas industry's revolution process for membrane separations followed by CO_2 removal in Company X (an Indonesian company at the oil and gas sector), which will eventually help to minimize CO_2 emissions. Natural gas is passed through a membrane separation unit, which is again dependent on emissive temperature with CO_2 levels being at 15.41% while being at 93 °F and at 12.07% while at 122 °F. Moreover, the gas following this gets treated with amine technology to reduce the CO_2 levels to the required levels. In conclusion operations produce high quality natural gas that complies with the maturing market as well as reduces carbon emissions. This is still a shallow representation on how the process amination steps demonstrate the possibilities of membrane technology. In this case, amination steps should be able to show how membrane technology can enhance the durability in effectiveness of the oil and gas industry.

In addition, the clean membranes conversions do not consume a lot of power and therefore lowers operational costs while enforcing the strict set environmental laws [41]. This may make them an attractive option for businesses keen on improving their economic status [42]. This dual-sided benefit accentuates the competitive significance of implementing gas separation technology in operating and developing innovations in the oil and gas industry [43]. Based on the book [44] as the general gas buyer specification as the world's parameter in the gas trading, there are some criteria that need to be fulfilled during the gas trading toward agreements. As the Fig. 1 shows, over all in the gas trading, the gas buyer restricted.

The illustration below on the Fig. 1 demonstrates the rationing of the composition of sales gas: water content, hydrogen sulfide, and carbon dioxide, as determined by different authorities.

Concerning the water content, the allowable value in the USA is 7 lb /MMCF (pounds per million cubic feet) but in Canada it is stricter at 4 lb /MMCF. Other areas may have different requirements as the equivalent restriction in SI is 0.16 g /S m^3 (grams per standard cubic meter). With respect to hydrogen sulfide (H_2S) the typical limit of 10 parts per million (ppm) may different some jurisdictions. Carbon dioxide (CO_2) on the other hand has a common limit of 2 mol % (percentage by mole) but this too can be different from one region to another. Meeting safety, environmental and operational standards before any gas is supplied needs such restrictions to be in place [45] (Fig. 2).

The implementation of advanced membrane technology in the oil and gas sector not only mitigates emissions but also yields substantial economic advantages by decreasing tax liabilities, especially in regions with carbon pricing frameworks [46, 47]. The carbon market system in Indonesia is becoming recognised as an instrument to address climate change and promote emission reductions [48, 49]. Presidential Regulation No. 98/2021 on carbon pricing establishes the basis for carbon trading, carbon taxes, and results-based rewards within the national emission reduction framework [50].

Indonesia has initiated a carbon tax system, imposing a levy of IDR 30,000 per kilogramme of CO_2 equivalent (CO_2E), with intentions for incremental increases thereafter [51]. This tax targets sectors that beyond established emission thresholds, necessitating the use of devices that mitigate carbon emissions for corporations [52]. Organisations that can exhibit reduced emissions, for instance, by implementing membrane technology for CO_2 separation, may substantially diminish or eradicate their carbon tax obligations [53, 54]. Moreover, these corporations may engage in carbon trading markets by selling surplus emission permits or creating carbon credits through verifiable emission reductions, which may be exchanged with other organisations [55].

Indonesia's carbon market facilitates the monetisation of emission reductions [56]. Companies that implement emission-reduction technology, such as CO_2 membrane systems, can engage in both national carbon trading programs and worldwide voluntary carbon markets [57]. CO_2 collected during the separation process can provide carbon credits if accurately documented and validated under globally recognised systems such as the validated Carbon Standard (VCS) or Gold Standard [58]. These credits can

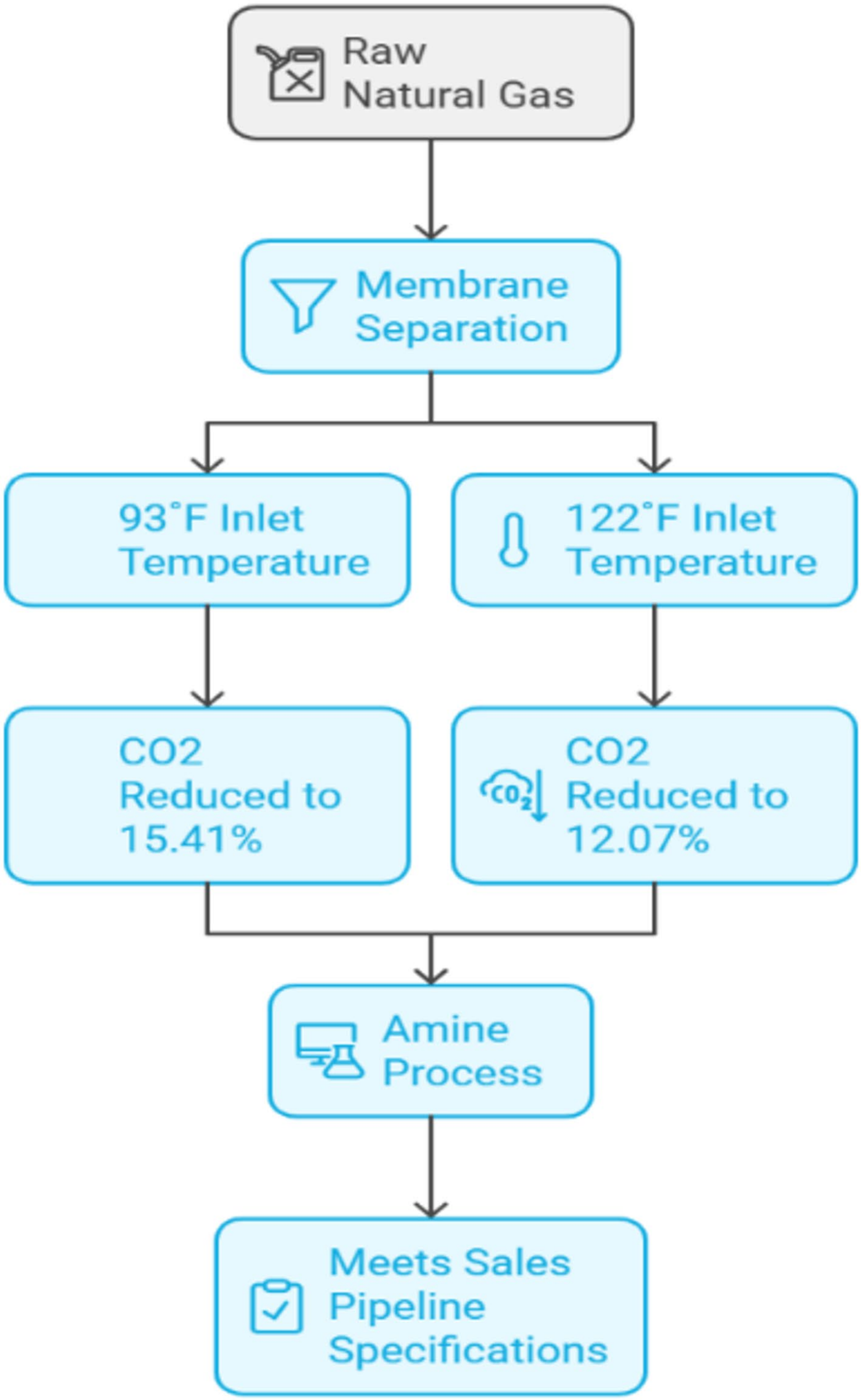

Fig. 1 Diagram of raw gas treatment process. *Source* Company X with own clarification

subsequently be sold to other firms requiring emissions offsets, so generating a potential cash stream [59].

CO_2 membrane technology not only mitigates tax obligations and capitalises on carbon markets but also complies with Indonesia's NDC objectives under the Paris Agreement [60]. By diminishing emissions and employing collected CO_2 for value-added

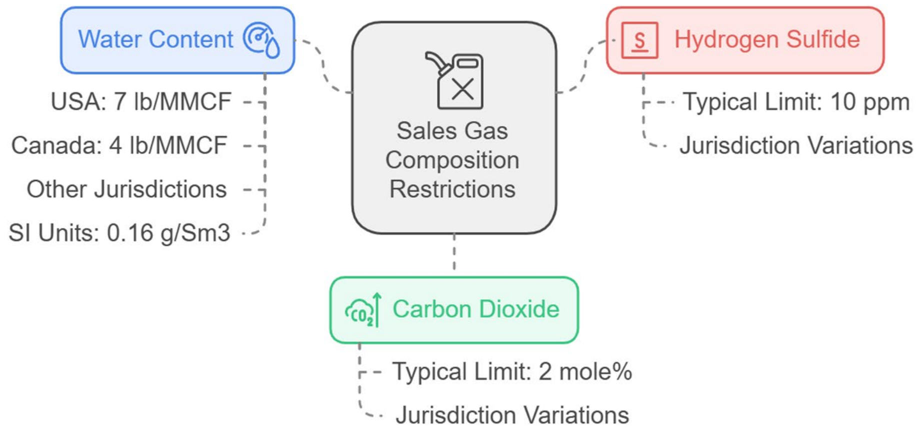

Fig. 2 Gas buyer specification. *Source* Own elaboration

applications such as better oil recovery, synthetic fuels, or building materials—companies boost them [61]. The objective of this paper is to assess the efficacy of the carbon tax reduction achievable by Company X through the implementation of membrane technology to mitigate greenhouse gas emissions in its operations, as well as to explore the potential additional avenues for converting CO_2 emissions into alternative products to enhance collaboration and increase company revenue.

Beyond the benefits of the membrane technology, however, there are also barriers, such as high investment price [62]. This study aims to compare its economic balance through a cost–benefit model calculation through a case study at an Indonesian gas producer company (Company X).

The rest of the paper is structured as follows. Section 2 presents the methodology, including the short introduction of Company X, including the carbon-dioxide reduction potential by using the membrane technology, and the scenarios of the cost–benefit analysis, including data sources. Section 3 presents the results, including per ton and absolute cost–benefit accounts for Company X. Section 4 discusses findings and elaborates on additional benefits and barriers related to the potential of the membrane technology in Indonesia. Section 5 concludes and raises some future research directions.

2 Material and method

2.1 Profile of the sample company—company X

Company X is an American company that manages one of the natural gas reserves from the Sumatera Island rock formation as corridor blocks that is categorized as one of the giant gas reserves in Indonesia. Company X has been conducting exploration and production in Indonesia since 2002, and specifically for the fields it operates, it has a 20 year contract agreement with the government. Company X only produces gas wells in fields located on land, with its gas production supporting the second largest national gas consumption in Indonesia, its gas is not only used in Indonesia but also exported to neighbouring countries in Southeast Asia. Typical gas fluid produced by Company X is highly corrosive or sour gas types with very high CO_2 levels. It is a reason why the Company X installed CO_2 membrane technology to reduce the gas content in the gas flow to fulfil the buyer's need and gas sales specification and reduce the environmental effects due to the release of CO_2 into the air as well.

Although Company X's decision on implementing the membrane technology is based on a complex decision, a model calculation is presented on the cost–benefit impacts on the company, when carbon pricing is also considered on the result section.

2.2 Data collection

Data used for the model calculation presented in this study is based on three types of data: (i) input for calculating the CO_2-reduction potential at Company X as a result of the membrane technology; (ii) Capture costs of the membrane technology, (iii) financial benefits or avoided costs through reduced CO_2-emissions, if the price of carbon is also considered. Moreover, the membrane utilized by Company X functions through a molecular sieving mechanism, employing a polymeric material as its medium. Due to the confidential nature of the data and the paucity of available information from Company X, further elaboration on the intricacies of the membrane technology was not possible.

Input data for the carbon reduction potential was obtained directly from Company X. To support the analysis of this research, important data are used such as the table of component of gas from the total daily production from the field operated by the company of 1015 million metric MMSCFD from the Company X report and site inspection through the control production room.

Capture costs of the membrane technology may vary based on different factors [63], as it is covered in literature, the extant research on techno-economic analysis indicates that membrane-based CO_2 capture in the oil and gas sector generally ranges mostly around 20–50 USD per ton of CO_2 [64–67]. Specific applications in liquefied natural gas (LNG) have been documented to report costs of approximately 13–14 USD per MMBtu [68], inclusive of sequestration which served as a benchmark for building scenarios. The variations highlighted in this study underscore the influence of technological specifications, regional economic factors, and operational contexts [69–71]. In accordance with the prevailing focus of the study on Indonesian conditions and the objective of investigating optimistic-to-moderate scenarios, the baseline cost range of 20–50 USD per ton of CO_2 is deemed suitable, especially in the context of regulatory and economic assessments [69–72]. This determination is made with the acknowledgment of the broader variability reported in global literature. To refine the scenarios, purchasing power parity (PPP) factors were also applied, with an average of 0.65 in Indonesia based on World Bank Data [73]. The selected factor of 0.65 signifies the present national PPP conversion for capital and operational expenditures in industrial projects in Indonesia. It should be noted that PPP values may vary by sector and area. In the absence of comprehensive local cost benchmarks for membrane technology adoption, this value serves as a practical yet acceptable foundation for early cost estimations in the absence of more particular data.

The benefits or savings in this study are considered as the avoided carbon tax per ton in Indonesia of IDR 30,000 converted to USD of circa 2 USD per ton was obtained from the policy decided by the Indonesian government [74]. However, if other large economies are considered, it is clear that many of them use much higher carbon tax rates (or, in case of tradable quotas, market quota prices are much higher).

This may forecast an increased tax rate in Indonesia as well in the future, so we considered carbon price in other key economies as well as scenarios. In the EU Emission Trading Scheme, the current quota price is circa 66.19 Euros (recorded on April 2025), equals to 76.12 USD per ton [75, 76]. In the United States of America, there is no central carbon pricing scheme, so we considered the initiative in California, where carbon quota price is 60.47 USD per ton [77]. In China, there is also a carbon trading scheme in force for part of the country, with quota prices 94.73 CNY or 14.95 USD per ton [78].

2.3 Method

To support this study, the research adopts an empirical carbon pricing and cost–benefit analysis (CBA) framework with some scenarios. First, the annual carbon reduction potential of the membrane technology was calculated. The data of gas mixture component including the impurities was recorded through the site inspection on the Company X's control room and it's a real-time operational data procured from the production facility's centralized control systems, which is displayed on the control room panel as a digital twin technology, with the total gas production 1015 MMSCF per day. The Digital Twin (DT) technology is a real-time remote observation of system processes [79]. A DT is a dynamic digital copy of a real asset, process, system, or product, created with a specific purpose in mind [80]. It connects the physical and digital domains, enabling seamless data and information flow between locations for example, between an oil and gas site and the office.

The composition of raw natural gas is produced by company X indicates a primary carbon dioxide (CO_2) content of 34% as shown on the table below, which necessitates reduction due to its contribution to greenhouse gas emissions and its non-compliance with pipeline specifications. The predominant component is methane (CH_4), accounting for 64.670% of the mixture. This component is of significant economic value due to its role as a primary fuel. Other components, including heavy hydrocarbons (C_2 to C_{7+}), nitrogen (N_2), and water (H_2O), necessitate additional treatment to remove impurities and enhance gas quality. Notably, hydrogen sulfide (H_2S), though present in trace amounts (0.004%), poses a significant hazard due to its toxicity and must be removed. The negligible presence of glycol (0.000%) indicates that this gas is devoid of any contamination from the process of dehydration.

The significance of technologies such as membranes and amine processes is underscored by these findings. These technologies are instrumental in separating CO_2, treating other components, and ensuring that natural gas meets market specifications while reducing environmental impacts. For the detail of gas mixture can be found below the Table 1 below.

Regarding the calculation of carbon emissions, we use several stages: first, convert the total gas production in MMSCFD units into moles per day units assuming the ideal gas law in standard conditions with a temperature of 60 °F and a pressure of 1 atm. Second, calculate moles of CO_2 by multiplying the percentage of CO_2 by the total moles of gas, third calculate the mass of CO_2 by multiplying the total moles of CO_2 by the molar mass of CO_2 so that the mass of CO_2 is obtained in kilograms per day, fourth convert the mass of CO_2 from kilograms per day to tons per day, the next stage to get annual CO_2 emissions, then the mass is multiplied by 365 days so that emissions per year are obtained, and finally calculate the annual carbon tax per year and PPP adjusted cost. The following of equations from the stages above is explained further below:

1. Convert the unit of MMSCFD into moles per day unit where the 1 standard cubic foot (SCF) = 1.263 mol gas at standard temperature and pressure [81]

Table 1 Raw natural gas composition of company X

Component	Percentage (mole%)
CO_2	34.465
H_2S	0.004
N_2	0.446
C_1	64.670
C_2	0.308
C_3	0.025
i-C_4	0.008
n-C_4	0.004
i-C_5	0.008
n-C_5	0.004
n-C_6	0.008
C_{7+}	0.030
H_2O	0.020
glycol	0.000

The amount of gas = Total mass flow of gas per day in SCF × 1.263 mol/SCF

2. Calculate moles of CO_2 by multiplying the percentage of CO_2 by the total moles of gas
   The amount of CO_2 mol = The percentage of CO_2 fraction x the amount of gas.
3. Calculate the mass of CO_2 in kilograms unit
   Where the molar mass (Mr) of CO_2 = 44 g/mol = 0.044 kg/mol,
   The mass of CO_2 in kg = Mr of CO_2 × the amount of CO_2 mol
4. Convert the mass of CO_2 from kilograms per day to tons per day
   The mass of CO_2 in ton = The mass of CO_2 in kg/1000 kg/ton
5. Calculate the annual mass of CO_2 in ton unit
   The annual mass of CO_2 = The mass of CO_2 in ton unit × 356 days
6. Calculate the annual carbon tax in USD per year
   The annual carbon tax = The annual mass of CO_2 in ton × CO_2 Carbon tax rate of Indonesia
7. Calculate the PPP adjusted cost with PPP factor 0.65
   PPP adjusted cost = The annual carbon tax/PPP factor

Upon completion of the calculation, a comparison is made between the initial emission amount and the remaining quantity resulting from the installation of the CO_2 membrane. This comparison reveals a significant reduction in CO_2 levels, from an initial 34% to approximately 12%, with a capture percentage of approximately 22%. The results of this analysis are presented in the results section.

Next, the cost–benefit analysis per ton of carbon-dioxide reduction was calculated for the different scenarios. On the cost side, we used the 20–50 USD range, with also adding an average (USD 35) scenario. Additionally, we also used scenarios of multiplying all the previous ones (20, 35 and 50 USD) with the PPP factor of 0.65, indicating the lower prices in Indonesia. On the benefit side, the current Indonesian as well as foreign carbon prices were considered, resulting a per ton cost–benefit balance when deducing the costs from the savings.

As the last step of the model calculation, the carbon reduction potential data of Company X were multiplied by the cost–benefit balance data of the different scenarios, indicating absolute saving potentials among them.

Table 2 Company X carbon emissions overview

Parameter	Content (%)	Quantity per year (Ton)	Carbon tax cost per year (USD)	PPP adjusted cost (USD)
Initial CO_2 emission	34.4465	7,095,666	14,191,333	21,832,821
Remaining CO_2 emission	12	2,471,891	4,943,782	7,605,819
CO_2 reduction	22.4465	4,623,775	9,247,551	14,227,001

Table 3 The cost–benefit balance of the membrane technology per ton of carbon dioxide reduction (USD per ton if not stated otherwise)

Savings/Benefits (S—right)		S1 (Indonesia—IDR30,000 = 2 USD per ton)	S2 (China—2025, 13 EUR = 14.95 USD per ton)	S3—USA (California—2025 in USD per ton)	S4—EU ETS (66.19 EUR = 76.12 USD per ton)
Capture costs (CC—below)		**2**	**14.95**	**60.47**	**76.12**
CC1 (LOW)	20	− 18	− 5.05	40.47	56.12
CC2 (HIGH)	50	− 48	− 35.05	10.47	26.12
CC3 (AVG)	35	− 33	− 20.05	25.47	41.12
CC4 (LOW-PPP)	13	− 11	1.95	47.47	63.12
CC5 (HIGH—PPP)	32.5	− 30.5	− 17.55	27.97	43.62
CC6 (AVG-PPP)	22.75	− 20.75	− 7.8	37.72	53.37

3 Results

3.1 Annual carbon dioxide reduction potential at company x

Table 2 provides an overview of carbon dioxide reduction potential and related carbon costs at Company X.

As illustrated in the above table, it can be deduced that, in the absence of membrane technology, Company X will generate 7,095,666 tons per year. When a carbon tax price of 2 USD per day is applied in Indonesia, Company X will incur an incentive bill of 14,191,333 USD per year. This figure will be even more substantial when the PPP factor of 0.65 is taken into account, resulting in higher an annual incentive bill of 21,832,821 USD. Nevertheless, a substantial decrease was observed subsequent to the implementation of CO_2 membrane technology, amounting to 22.4465%, equivalent to 4,623,775 tons per year. This results in a cost reduction for Company X of 9,247,551 USD per year. Ultimately, the Company compensates the Indonesian government with a yearly sum of 4,943,782 USD. This compensation is derived from emissions that are not offset, which account for 12% of the total emissions, amounting to 2,471,891 tons of CO_2 per year.

3.2 Cost–benefit balance of the membrane technology per ton of carbon dioxide reduction

The following Table 3 presents a summary of the cost–benefit balance per ton of CO_2 for the various scenarios that were considered. It also includes the different carbon prices between counties and regions. This is based on the assumption that Indonesia does not currently have a fully operational national carbon pricing mechanism. For this reason, the European Union, California, and China can be referenced to provide relevant policy benchmarks. Due to their established carbon markets and climate commitments, these regions represent different regulatory designs and stages of market maturity. As such, they can be useful references for projecting potential carbon pricing scenarios in Indonesia. This selection is further substantiated by Indonesia's escalating congruence with

Table 4 Absolute cost–benefit balance of the membrane technology at Company X (USD per year)

Savings/Benefits (S, right)		S1 (Indonesia—2025 carbon tax rates)	S2 (China—2025 carbon quota prices)	S3—USA (California)—2025 carbon quota prices	S4—EU ETS 2025—(2025 carbon quota prices)
Capture costs (CC—below)		**9,247,551**	**69,125,445**	**279,599,710**	**351,954,862**
CC1 (LOW)	**92,475,511**	**− 83,227,960**	**− 23,350,066**	**187,124,198**	**259,479,350**
CC2 (HIGH)	231,188,779	− 221,941,228	− 162,063,334	48,410,930	120,766,082
CC3 (AVG)	161,832,145	− 152,584,594	− 92,706,700	117,767,564	190,122,716
CC4 (LOW-PPP)	60,109,082	− 50,861,531.51	9,016,362	219,490,627	291,845,779
CC5 (HIGH—PPP)	150,272,706	− 141,025,155	− 81,147,261	129,327,003	201,682,155
CC6 (AVG-PPP)	105,190,894	− 95,943,343	− 36,065,449	174,408,815	246,763,967

global climate objectives, encompassing the revised NDC under the Paris Agreement and the national Emissions Trading System (ETS) initiative, as delineated below.

As illustrated in Table 3, there are five columns. The first column corresponds to the capture cost, which is further categorized into CC1 to CC6, contingent on the price level and the influence of the PPP factor. The second column is designated for the management or capture of CO_2 emissions, expressed in USD units per ton for each capture cost. For the next columns, the carbon prices for each scenario are presented, encompassing multiple countries and regions, notably Indonesia, China, [79] California [80] and the European Union [81]. These scenarios are denoted by S1, S2, S3, and S4, respectively. As demonstrated in the preceding table, a comparative analysis of capture costs (CC1, CC2, CC3) across low, average, and high levels, augmented by the incorporation of PPP factors (CC4, CC5, CC6) per ton, reveals a PPP factor price range that extends from low to high, with a mean value of 0.65 and a standard deviation of 0.02. The findings demonstrate considerable variation in the outcomes of the comparison between the capture cost and the carbon tax price for each scenario. This variation is represented by the use of red and green colors, with negative and zero signs. In instances where the red number and negative sign are present, it indicates that no cost savings are realized. This signifies that the capture cost price exceeds the carbon tax price. For instance, in scenarios 1 and 2 (S1 and S2), the difference is negative and red for Capture cost CC1.

The results of the difference between the capture cost and the carbon tax price are indicative of a cost saving from the separation and capture process of CO_2. For instance, when the CC3 price of 50 USD per ton is juxtaposed with the carbon tax price in California and the European Union zone, the discrepancy is 25.47 USD per ton and 41.12 USD per ton, respectively. It can be concluded that the highest saving cost is in capture cost 4 (CC4), which exhibits a low PPP factor compared to the carbon tax price of the fourth scenario (S4) for the European Union region of 63.12 USD per ton. Conversely, the lowest non-saving cost value is in the difference between CC2 and S1 of − 48 USD per ton. However, an examination of the cost–benefit analysis for column S1, with a particular focus on Indonesia, reveals that the current price remains unfavorable due to the modest value assigned to the carbon tax.

3.3 Absolute cost–benefit balance of the membrane technology at company x in different scenarios

Based on the calculation presented in the previous subsection, Table 4 provides the cost–benefit balance of the model calculation for the different scenarios.

Table 4 is a continuation of Tables 2 and 3 It utilizes the CO_2 reduction value from Table 2, which is 9,247,551 tons per year, to calculate the avoided emission captured. The quantity of CO_2 emissions in tons per year must be multiplied by each value in the capture cost column (CC1–CC6) and the scenario column (S1–S4). It can be concluded that the CC4 and S4 scenarios present the highest potential for cost savings, with an estimated annual cost reduction of 291,184,779 USD per year. Conversely, the CC2 and S1 scenarios demonstrate the lowest potential for cost savings, with an estimated annual cost increase of – 221,941,228 USD per year.

4 Discussion

4.1 Future directions in membrane technology-based carbon-dioxide reduction costs and benefits

The model calculation in this study revealed that CO_2 reduction through the membrane technology is currently not financially returnable in an Indonesian context, considering the large per ton reduction costs and the low tax rates. However, both costs of the technology and savings through the carbon tax may change in future. Moreover, the sophistication in manufacturing and material selection will greatly contribute to cost reductions, by using cheaper materials and methods for CO_2 capture [82]. In addition, increasing energy efficiency can reduce operational costs for the use of CO_2 membrane technology [83],

In terms of benefits (through avoided tax payment), international practice shows that there are many other countries and regions (all sample areas considered among the scenarios—the EU, the United States and China) where carbon prices are already much higher than in Indonesia. Furthermore, carbon prices in those areas have been increasing continuously since their introduction [52]. Parallel, Indonesian carbon tax rates may also increase significantly in future [84]. Because the fact, the carbon tax price in Indonesia currently is far lower the global average of 32 USD per ton [52]. Furthermore, this analysis emphasizes the significance of market-based instruments, such as carbon pricing, in addressing climate change. While carbon taxes provide price certainty and predictable revenues for governments, the ETS also offers a reduction in emissions and may be more appropriate for industries with variable abatement costs. In the context of Indonesia, which has recently fully implemented the ETS program in 2025 [85] this development offers a novel approach to reducing carbon emissions, emphasizing the importance of fiscal stability and sectoral adaptability. The combined use of these instruments has the potential to offer a pragmatic path towards decarbonization in the oil and gas sector.

Based on the tendencies above, it is highly possible that future tendencies make membrane technology financially beneficial for Company X, or in an Indonesian context, only from the perspective of reduced carbon-dioxide. Furthermore, in countries with already high carbon prices (tax or quota price), the financial benefits of membrane technology already increase its cost.

4.2 Additional benefits of the membrane technology

Beyond the financial savings of reduced carbon costs, the membrane technology offers other benefits through the capture of concentrated CO_2, even if those impacts are hard to monetize. For example, during enhanced oil recovery (EOR) operations where carbon dioxide is injected into the oils reservoir to increase hydrocarbon extraction, the byproducts from EOR can also be used to further purify the carbon dioxide [86]. The utilization of membrane technology is paramount for effective EOR operations and maximizing oil displacement efficiency, as it can capture CO_2 and deliver it with a high degree of purification (> 99.7%), which is essential for these processes [87–89]. Furthermore, if the oil price is approximately 27.9 USD per barrel, the utilization of captured CO_2 for EOR will generate revenue from additional oil production, thereby offsetting the cost of capture and storage [88]. This assertion is supported by extant studies demonstrating that the additional oil revenue can fully cover the cost of capture [87, 88]. In addition, clean CO_2 can be used in the food and drinks industry, chemical, construction (polymer) industries, and for synthetic fuels [90]. All of these make an asset instead of a nuisance, and along with sustainability, creates and economic opportunity [91]. Carbon capture and storage (CCS) presents an additional strategic use of isolated CO_2 [92]. Moreover, involvement in carbon sequestration initiatives can provide carbon credits, which are tradable in carbon markets, so offering an extra and consistent cash stream for the firm [93].

CO_2 possesses several industrial applications, hence enhancing its economic potential [94]. In the food and beverage sector, it is utilised for carbonation, whilst in chemical manufacturing, it functions as a significant feedstock [95]. Moreover, CO_2 may be integrated into building materials such as concrete, resulting in novel products that mitigate environmental effect [96]. These apps enable Company X to broaden its market presence and augment its income sources via sustainable practices.

4.3 Implications for the Indonesian oil and gas sector

While the present analysis focuses on Company X, the insights gained are relevant to other actors in the Indonesian oil and gas sector. A considerable number of companies in the industry encounter analogous challenges pertaining to carbon taxation and emission control. The membrane-based emission reduction model presented in this study demonstrates a high degree of adaptability to diverse operational conditions, suggesting its viability for implementation across the sector. It is recommended that companies with high gas production that are afflicted with CO_2 impurity and sour gas, as well as companies that engage in oil production with CO_2 associated with it, employ this membrane technology. Moreover, given the mounting governmental emphasis on climate mitigation strategies, such technologies may become more economically viable in the near future.

4.4 Limitations

This study presented a model calculation on a specific technology for a sample company (Company X) to model different scenarios based on different cost and savings data. This calculation helps the better understanding of the dynamics of financial returns of the membrane technology in relationship to carbon prices, it is based on oversimplification, and thus the interpretation of findings has to be considered with caution.

Costs of the membrane technology are extremely project/company specific; this is the reason we used rather a wide range of scenarios from academic literature for the per ton reduction costs. In a specific case, a more detailed calculation (including initial investment costs, operation costs, depreciation etc.) has to be performed [97]. Furthermore, higher carbon costs do neither guarantee the short-term increase of the carbon-dioxide tax rate in Indonesia. Additionally, even this paper focused on the membrane technology, there may be different alternative technological solutions with potentially lower costs A notable example is bioenergy with carbon capture and storage (BECCS), which has a cost of 30 USD per ton and the advantage of optimized logistics and infrastructure on site [98], that may make it less competitive.

This research employs cost estimates based on academic literature. However, it is acknowledged that a more precise cost assessment would necessitate thorough process models on a bottom-up basis with site-specific economic characteristics and sensitivity testing. Furthermore, we also consider the PPP value of 0.65 we used for the Indonesian context to be an indicative proxy rather than an exact estimate. We urge future studies to employ a thorough techno-economic analysis within the context of Indonesian oil and gas.

Beyond these limitations, however, the model calculation presented here can add more insights of the future cost–benefit balance of the membrane technology both in an Indonesian context as well as in the context of countries with higher (or similar) carbon prices.

5 Conclusion

This study aimed to develop a model calculation to assess the financial viability of implementing the membrane technology for reducing carbon dioxide emissions in the oil and gas industry within an Indonesian context. Based on the findings of the model calculation, it seems that at the level of current technology and carbon prices in Indonesia, it does not pay back to implement the membrane technology only from a carbon cost saving perspective. However, if we consider expectedly higher carbon prices, like in the EU and US (California), or partly in China, a possible direction in future also for Indonesia, as well as the potential in technological development (resulting in lower capture costs of the technology), the financial viability of the membrane technology is expected to improve.

The relevance and importance of the cost–benefit analysis scenarios for Indonesia lies in the creation of a new policy framework. It is crucial to achieve a balance in carbon pricing: excessively low carbon prices (like the current one) may undermine a country's commitment to combating climate change, while overly high carbon tax rates could hinder economic growth by stalling monetization processes. Therefore, careful consideration must be given to determining the ideal and optimal carbon tax price that supports both environmental sustainability and economic progress. This approach will enhance the attractiveness and competitiveness of Indonesia's carbon market on a global scale.

Although this study considered an Indonesian context, as a future research direction, other countries, contexts and scenarios can be considered to gain a better understanding on the financial viability of the membrane, or other innovative technologies. This can be especially useful in countries or sectors heavily reliant on hydrocarbon exploration and production.

As this study presented a model calculation, a further future research direction can be a more detailed, and company specific estimation of the carbon capture costs through the membrane technology in different context and thus explore more detailed results on its financial aspects.

Author contributions

Muhammad Raynaldi: Conceptualization, Methodology, Writing—original draft. Gábor Harangozó: Conceptualization, Methodology, Writing and Supervision.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not Applicable.

Consent to participate

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Competing interest

The authors declare no competing interests.

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