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Article *in* Carbon Management · February 2019

DOI: 10.1080/17583004.2018.1553435

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This is an author generated post-print of the article "Roussanaly, S., 2019. Calculating CO_2 avoidance costs of Carbon Capture and Storage from industry. Carbon Management, 1-8." Copyright 2019 Published by Taylor & Francis Online. The final publication is available at **https://doi.org/10.1080/17583004.2018.1553435**.

Abstract

This work discusses methods for calculating the CO_2 avoidance cost for Carbon Capture and Storage from the non-power generation industry. Unlike the power generation sector, three calculation methods are often used to evaluate the CO_2 avoidance cost in the case of CCS from industrial sources. However, each of these methods relies on different assumptions of which potential users are not always aware. The links between these three methods are here presented and verified over an illustrative case to highlight the conditions that are required to ensure their reliable use, as well as their associated shortcomings. Finally, the basis to ensure the selection of the CO_2 avoidance cost calculation method that is both valid and most efficient for cases considered by potential users are presented.

Keywords: Carbon Capture and Storage (CCS); Industry; CO_2 avoidance cost; Techno-economic; Methodology.

Abbreviations: CCS, carbon capture and storage; CAPEX, capital expenditure; FCC, fluid catalytic cracker; OPEX, operating costs; TCR, total capital requirement.

NOMENCLATURE

Annual $OPEX_{CCS\ implementation}$	Additional annual operating cost related to CCS implementation ($/y)
D	Discount rate (%)
i	Year index (-)
$(LCOE)_{CCS}$	Levelised cost of electricity of the power plant with CCS ($/MWh)
$(LCOE)_{ref}$	Levelised cost of electricity of the power plant without CCS ($/MWh)
$(LCKM)_{CCS}$	Levelised cost of key material(s) of the industrial plant with CCS ($ per unit of key material)
$(LCKM)_{ref}$	Levelised cost of key material(s) of the industrial plant without CCS ($ per unit of key material)
NPV_{CCS}	Net present value of costs of the industrial plant with CCS ($)
NPV_{ref}	Net present value of costs of the industrial plant without CCS ($)
$(t_{CO2})_{CCS}$	Annual amount of CO_2 emissions of the industrial plant with CCS (t_{CO2}/y)
$(t_{CO2})_{ref}$	Annual amount of CO_2 emissions of the industrial plant without CCS (t_{CO2}/y)
$(t_{CO2}/MWh)_{CCS}$	CO_2 emission intensity of the power plant with CCS per amount of energy produced (t_{CO2}/MWh)
$(t_{CO2}/MWh)_{ref}$	CO_2 emission intensity of the power plant without CCS per amount of energy produced (t_{CO2}/MWh)
$(t_{CO2}/U_{KM})_{CCS}$	CO_2 emission intensity of the industrial plant with CCS per unit of key material (t_{CO2} per unit of key material)
$(t_{CO2}/U_{KM})_{ref}$	CO_2 emission intensity of the industrial plant without CCS per unit of key material (t_{CO2} per unit of key material)
$TCR_{CCS\ implementation}$	Total capital requirement linked with CCS implementation ($)
$(U_{KM})_{CCS}$	Annual amount of key material(s) produced or consumed by the industrial plant with CCS (unit of key material per year)
$(U_{KM})_{ref}$	Annual amount of key material(s) produced or consumed by the industrial plant without CCS (unit of key material per year)

1 INTRODUCTION

Carbon Capture and Storage (CCS) from power generation facilities in order to reduce the climate impact of the power sector has initially been the primary focus of CCS research in the last decades [1]. However, over the past decade, the interest in CCS from industry has greatly increased, and CCS is now regarded as an unavoidable measure to decarbonise (non-power generation) industry [2]. The industrial sector is responsible for roughly 21% of global greenhouse gases emissions [1]. Furthermore, several industries like cement, steel, refining and fertilizers produce significant CO_2 emissions that are inherent to their operations and cannot be eliminated without CCS.

Compared to CCS from power generation, CCS from industry can benefit from several advantages. First, as illustrated by Berstad et al. [3], industrial CO_2 sources, such as cement, steel, hydrogen, may have high CO_2 contents, and thus result in lower costs of CO_2 capture. Secondly, in some cases, waste heat from the industrial plant itself can be used to reduce the energy and cost penalties of CO_2 capture. Furthermore, in comparison with power plants, whose electricity and CO_2 emissions vary significantly throughout the year, industry tend to have a more stable productions over time, which enables high utilisation rates of the CCS infrastructure. Finally, although industrial CO_2 emissions may be smaller, significant economies of scales in transport and storage can be achieved through industrial clusters. As a consequence of these advantages, eight of the ten CCS plants which have come into operation since 2013 deal with industrial emissions (natural gas processing, hydrogen, fertilizer, chemical, iron and steel). Finally, this focus has also been reflected through extensive research to implement energy- and cost-efficient CCS from industrial sources of emissions [4, 5].

However, in comparison with the power generation sector, it is worth noting that several methods have been used to evaluate the CO_2 avoidance costs of CCS from industry*. These different methods have different advantages, but more importantly, they rely on different assumptions whose implications are not always explicit and understood by potential users. This can lead, in practice, to questions regarding the best method to calculate CO_2 avoidance costs of CCS from industry. This work therefore presents each of the CO_2 avoidance cost calculation methods, before discussing their respective necessary assumptions, limitations and advantages, as well as their comparison over an illustrative case. Finally, the basis to ensure the selection of the CO_2 avoidance cost calculation method that is both valid and most efficient for cases considered by potential users are presented.

2 METHODS FOR CALCULATING CO_2 AVOIDANCE COST

Before describing the different methods used to calculate the CO_2 avoidance cost of CCS from industry, it is important to remember the only method used in the case of CCS from the power generation industry. In this case, the CO_2 avoidance cost is calculated based on the cost and CO_2 emission intensity of the electricity generated with and without CCS as shown in Equation 1 and previously defined by the IPCC [6]. This method is derived from the equalisation of the net present values of costs of the power plant with and without CCS.

$$\text{CO}_2\text{ avoidance cost} = \frac{(\text{LCOE})_{\text{CCS}} - (\text{LCOE})_{\text{ref}}}{(\text{t}_{\text{CO2}}/\text{MWh})_{\text{ref}} - (\text{t}_{\text{CO2}}/\text{MWh})_{\text{CCS}}} \quad (1)$$

Where:

- $(\text{LCOE})_{\text{ref}}$ is the levelised cost of electricity of the power plant without CCS
- $(\text{LCOE})_{\text{CCS}}$ is the levelised cost of electricity of the power plant with CCS
- $(\text{t}_{\text{CO2}}/\text{MWh})_{\text{ref}}$ is the CO_2 emission intensity of electricity of the power plant without CCS
- $(\text{t}_{\text{CO2}}/\text{MWh})_{\text{CCS}}$ is the CO_2 emission intensity of electricity of the power plant with CCS

Meanwhile, in the case of CCS from industrial sources, three different methods are commonly used in the literature in order to calculate the CO_2 avoidance cost including CO_2 capture, transport and storage. However, while these three methods aims at calculating the same cost metric (CO_2 avoided cost), each of these methods relies on different assumptions of which potential users are not always aware.

* Please not here than the term industry here refers to the non-power generation industry.

The first one, here referred as "exhaustive" method, is derived from the power generation calculation method. In this method, the CO_2 avoidance cost is calculated based on the cost and CO_2 emission intensity of the "key material(s)" of the industrial plant with and without CCS [4, 5] as shown in Equation 2. It is worth noting that in this case, the key materials may be the main product, the main input material of the plant, or even a combination of products. A list of example of "key materials" which are commonly used for different industrial plants is presented in Table 1.

$$CO_2 \text{ avoidance cost} = \frac{(\text{LCOKM})_{\text{CCS}} - (\text{LCOKM})_{\text{ref}}}{(t_{CO2}/U_{KM})_{\text{ref}} - (t_{CO2}/U_{KM})_{\text{CCS}}} \quad (2)$$

Where:

- $(\text{LCOKM})_{\text{ref}}$ is the levelised cost of the key material(s) of the industrial plant without CCS
- $(\text{LCOKM})_{\text{CCS}}$ is the levelised cost of the key material(s) of the industrial plant with CCS
- $(t_{CO2}/U_{KM})_{\text{ref}}$ is the CO_2 emission intensity of the industrial plant without CCS per unit of key material(s)
- $(t_{CO2}/U_{KM})_{\text{CCS}}$ is the CO_2 emission intensity of the industrial plant with CCS per unit of key material(s)

Table 1: Key material commonly considered for the different types of industrial plant

Type of industrial plant	Commonly used key material (unit)
Cement plant	Amount of cement produced (in tonnes of cement)
Steel plant	Amount of steel produced (in tonnes of steel)
Refinery plant	Amount of crude oil processed (in barrels of oil)
Hydrogen plant	Amount of hydrogen produced (in tonnes of hydrogen)
Natural gas processing plant	Amount of natural gas processed (in normal cubic meter)

The second and third methods, here referred as "net present value" and "annualisation" methods, are similar to the approaches normally used to evaluate a production cost, such as the cost of electricity, as shown in Equations 3 and 4. These methods are derived from the unit cost calculation based on the discounted cash flow of implementing CCS. Unlike the "exhaustive" method, these exclude the cost of the industrial plant in which CCS is to be implemented and are not directly linked to the key material produced or consumed by the plant. For these reasons, both of these methods have been especially used to evaluate CCS for retrofit applications without modification of the industrial plant production.

$$CO_2 \text{ avoidance cost} = \frac{\text{Net Present Value of CCS implementation cost}}{\sum_i \frac{\text{Amount of } CO_2 \text{ emissions avoided by CCS implementation}(i)}{(1+d)^i}} \quad (3)$$

$$CO_2 \text{ avoidance cost} = \frac{\text{Annualised investment due to CCS implementation} + \text{Annual operating cost due to CCS implementation}}{\text{Annual amount of } CO_2 \text{ emissions avoided}} \quad (4)$$

An overview of calculation methods selected by different studies is presented in Table 2 by type of industrial plant.

Table 2: Calculation methods used in different studies in function of the type of industrial plant

Type of industrial plant	"Exhaustive" method	"Net present value" method	"Annualisation" method
Cement plant	Roussanaly et al. [7] IEAGHG [4] Cormos and Cormos [8]		Jakobsen et al. [9] Roussanaly and Anantharaman [10] Ho et al. [11]
Steel plant	IEAGHG [5]	Ho et al. [11]	Roussanaly and Anantharaman [10] Kuramochi et al. [12]
Refinery plant	Fernández-Dacosta et al. [13]	Ho et al. [11]	Roussanaly and Anantharaman [10] Anantharaman et al. [14] Kuramochi et al. [12]
Hydrogen plant	IEAGHG [15] Lin et al. [16] Riva et al. [17]		
Natural gas processing plant	Grande et al. [18]		

It is worth noting that in each of these three methods, the full CCS chain is here considered including CO_2 capture, transport and storage. However, it is worth noting that in some of the literature these equations are also used considering only CO_2 capture without CO_2 transport and storage. If CO_2 transport and storage is not included, the correct term for the cost metric calculation is cost of CO_2 captured as highlighted by Rubin et al. [19].

3 ASSUMPTIONS, ADVANTAGES AND LIMITATIONS BEHIND THE DIFFERENT CO_2 AVOIDANCE COST CALCULATION METHODS

Although these three methods for calculating the CO_2 avoidance cost appear to be significantly different, they are in fact linked. It is therefore important to understand the different assumptions that underlie each method, their respective advantages, and the limitations introduced by these assumptions.

Starting from the "exhaustive" calculation method, which is always valid, the "net present value" method can be obtained mathematically as long as two conditions are satisfied. First, the production of the industrial plant must not be impacted by the implementation of CCS. In such a case, the "exhaustive" calculation method can be simplified, as shown in Equations 5 to 8. Secondly, the additional costs and CO_2 emissions avoided due to the CCS implementation can be assessed separately from the industrial plant costs, as shown in Equations 8 and 9. It is worth noting that the costs evaluated must take into account not only the costs directly associated with the CCS infrastructure but also costs such as utilities production and integration of CCS with the production of the industrial plant.

Nonetheless, it is essential to bear in mind that these two conditions may not be met in every case. Indeed, certain combinations of CO_2 capture technologies and industrial plants may result in changes in the production of the industrial plant. For example, the integration of calcium looping capture with a cement plant results in a cement production increase, and implementation of oxy-combustion capture on a fluid catalytic cracker (FCC) in a refinery results in higher conversion yield of the FCC unit. Moreover, while assessing the additional costs and CO_2 emissions avoided of CCS implementation separately from those of the industrial plant itself should be achievable for post-combustion CO_2 capture or retrofit implementation cases, it may be more challenging in other cases. For example, in the case of hydrogen production with CCS based on protonic ceramic membranes, hydrogen production and CO_2 separation take place in the same unit. In such case, the costs of hydrogen production and CO_2 capture cannot be separated and the "exhaustive" calculation method must be used to calculate the CO_2 avoidance cost.

$$CO_2 \text{ avoidance cost} = \frac{(LCOKM)_{CCS} - (LCOKM)_{ref}}{(t_{CO2}/U_{KM})_{ref} - (t_{CO2}/U_{KM})_{CCS}} \quad (5)$$

$$CO_2 \text{ avoidance cost} = \frac{\frac{NPV_{CCS}}{\sum_i \frac{(U_{KM})_{CCS}}{(1+d)^i}} - \frac{NPV_{ref}}{\sum_i \frac{(U_{KM})_{ref}}{(1+d)^i}}}{\frac{\sum_i \frac{(t_{CO2})_{ref}}{(1+d)^i}}{\sum_i \frac{(U_{KM})_{ref}}{(1+d)^i}} - \frac{\sum_i \frac{(t_{CO2})_{CCS}}{(1+d)^i}}{\sum_i \frac{(U_{KM})_{CCS}}{(1+d)^i}}} \quad (6)$$

$$CO_2 \text{ avoidance cost} = \frac{\frac{NPV_{CCS}}{\sum_i \frac{(U_{KM})_{ref}}{(1+d)^i}} - \frac{NPV_{ref}}{\sum_i \frac{(U_{KM})_{ref}}{(1+d)^i}}}{\frac{\sum_i \frac{(t_{CO2})_{ref}}{(1+d)^i}}{\sum_i \frac{(U_{KM})_{ref}}{(1+d)^i}} - \frac{\sum_i \frac{(t_{CO2})_{CCS}}{(1+d)^i}}{\sum_i \frac{(U_{KM})_{ref}}{(1+d)^i}}} \quad (7)$$

$$CO_2 \text{ avoidance cost} = \frac{NPV_{CCS} - NPV_{ref}}{\sum_i \frac{(t_{CO2})_{ref}}{(1+d)^i} - \sum_i \frac{(t_{CO2})_{CCS}}{(1+d)^i}} \quad (8)$$

$$CO_2 \text{ avoidance cost} = \frac{\text{Net Present Value of CCS implementation cost}}{\sum_i \frac{\text{Annual amount of } CO_2 \text{ emissions avoided by CCS implementation}(i)}{(1+d)^i}} \quad (9)$$

Moreover, the "net present value" calculation method can be further simplified into the "annualisation" one, as shown in equations 10 to 13, if the annual operating costs and amount of CO_2 avoided are constant over the operating lifetime of the plant, as well as if the amount of CO_2 emitted (directly or indirectly) during the construction period can be excluded or neglected.
Although the first assumption appears simple, it means that the ramp-up in operations that are expected in the first years of operation of CCS systems are excluded. In practice, start-ups of both industrial plants and CCS demonstration projects has shown that such ramp-up in operations can be significant, and thus can have a non-negligible effect on the CO_2 avoidance cost. Furthermore, different CCS technologies can be expected to result in different ramp-up in operation due, for example, to different levels of integration with the industrial plant. Meanwhile, the second assumption is usually taken into account in the literature both for industrial and power plant cases, as the CO_2 emissions associated with construction are complex to evaluate, uncertain, currently not included in CO_2 emissions schemes and thus not financially valued. However, recent life cycle assessments of low climate impact technologies have shown that the climate impact associated with materials and construction can have a significant impact on the effective global warming potential of a technology and should thus be included when evaluating such concepts [20, 21]. Thus, to provide a complete picture of the cost of avoided CO_2 emissions by CCS, it is important to also take into account the CO_2 emissions related to the construction of the CCS system through, for example, hybrid life cycle assessment [22-25]. Moreover, the CO_2 emissions linked to the construction of such plant can be non-negligible and can vary significantly between CCS technologies, thus neglecting or excluding these emissions could also affect the comparison of CO_2 avoidance cost between different technologies.

$$CO_2 \text{ avoidance cost} = \frac{\sum_i \frac{TCR_{CCS\ implementation}(i) + \text{Annual } OPEX_{CCS\ implementation}(i)}{(1+d)^i}}{\sum_i \frac{\text{Annual amount of } CO_2 \text{ emissions avoided by CCS implementation(i)}}{(1+d)^i}} \quad (10)$$

$$CO_2 \text{ avoidance cost} = \frac{\sum_i \frac{TCR_{CCS\ implementation}(i) + \text{Annual } OPEX_{CCS\ implementation}}{(1+d)^i}}{\sum_i \frac{\text{Annual amount of } CO_2 \text{ emissions avoided by CCS implementation}}{(1+d)^i}} \quad (11)$$

$$CO_2\text{ avoidance cost} = \frac{\frac{\sum_i \frac{TCR_{CCS\ implementation(i)}}{(1+d)^i}}{\sum_i \frac{1}{(1+d)^i}} + \text{Annual } OPEX_{CCS\ implementation}}{\text{Annual amount of } CO_2 \text{ emissions avoided by CCS implementation}} \quad (12)$$

$$CO_2\text{ avoidance cost} = \frac{\text{Annualised investment due to CCS implementation} + \text{Annual operating cost due to CCS implementation}}{\text{Annual amount of } CO_2 \text{ emissions avoided}} \quad (13)$$

Where the annualised investment due to CCS implementation is defined as follow:

$$\text{Annualised investment due to CCS implementation} = \frac{\sum_i \frac{TCR_{CCS\ implementation(i)}}{(1+d)^i}}{\sum_i \frac{1}{(1+d)^i}} \quad (14)$$

Besides the limitations imposed by the assumptions that underlie each calculation method, it is also important to understand the advantages and drawbacks of each calculation method. As illustrated above, the "exhaustive" calculation method has the advantage of not relying on any of the above assumptions and being valid for all combinations of industrial plant and CCS technologies. However, this approach requires a significant amount of technical and cost data on the industrial plant considered, data that may not always be necessary to accurately evaluate the CO_2 avoidance cost. Besides the significant amount of efforts and resources that may, in some cases, be unnecessarily spent on the detailed technical and cost assessments of the industrial plant, such approaches may result in low-quality data being used for certain part(s) of the industrial plant, thus reducing confidence in the CO_2 avoidance cost estimated. Meanwhile, the "net present value" and "annualisation" calculation methods do not require the evaluation of the entire industrial plant with and without CCS, but only the CCS system itself, plus the costs of integration and potential modifications of the plant. These approaches can thus significantly reduce the resources spent in collecting data and/or calculating of the industrial plant. However, the "net present value" and "annualisation" calculation methods also have shortcomings, as the assumptions discussed above need to be met for the cases considered in order to ensure the validity of these two methods.

4 ILLUSTRATION

This section aims to illustrate, through an example, that the three calculation methods result in the same estimated CO_2 avoidance cost when the necessary assumptions are met. In order to do so, a case study is here considered. The case selected is based on previously published data [7] to ensure transparency and established estimates.

In this case, CO_2 is captured from a cement plant using a post-combustion amine system. For the sake of the exercise considered here, the CCS costs presented in Roussanaly et al. [7] are considered to include the whole CCS chain although they represent only the CO_2 capture and conditioning costs.

The key technical, cost and environmental data required for calculating the CO_2 avoidance cost are presented in Table 3. Finally, the economic evaluations are performed considering a discount rate of 8%, an operating lifetime of 25 years, and the first year of operation 1 as reference year for net present value calculations.

Table 3: Key technical, cost and environmental data of the considered case

	Cement plant without CCS	CCS implementation solely	Cement plant with CCS
Overnighted† CAPEX (M€)	217.6	125.0	342.6
Annual fixed OPEX (M€/y)	18.13	8.58	26.7
Annual variable OPEX (M€/y)	23.16	27.76	50.9
Annual cement production (Mt_{cement}/y)	1.36	-	1.36
Annual CO_2 emissions (Mt_{CO2}/y)			
of the cement plant without CCS	0.89	-	0.09
captured and stored	-	0.80	-
associated with CCS implementation	-	0.22	0.22
of the cement plant with CCS	-	-	0.31
Annual CO_2 emissions avoided (Mt_{CO2}/y)	-	-	0.58

Following the requirements for validity of the three calculation methods, the following assumptions are met:

1) The considered CCS implementation is not expected to impact the cement production
2) The costs associated with CCS can be assessed separately from the cement plant costs
3) The cement production, and thus CO_2 emissions without CCS, are assumed to be constant over the plant operating lifetime
4) The CO_2 emissions associated with the construction period are excluded.

- **Calculation method 1: "Exhaustive" method**

Based on the data presented in Table 3, the levelised cost of cement with and without CCS is evaluated to respectively 80.68 and 45.35 €/t_{cement}. Meanwhile, the CO_2 emission intensity of the industrial plant with and without CCS is evaluated to respectively 0.2264 and 0.652 t_{CO2}/t_{cement}. Using these numbers, the CO_2 avoidance cost evaluated with the "exhaustive" method is 83.0 €/$t_{CO2,avoided}$.

- **Calculation method 2: "Net present value" method**

Based on the data presented in Table 3, the net present value of CCS implementation costs is equal to 553.94 M€, while the net present value of avoided CO_2 emissions is equal to 6.673 $MtCO_{2,avoided}$. Using these numbers, the "Net present value" method results in a CO_2 avoidance cost of 83.0 €/$t_{CO2,avoided}$.

- **Calculation method 3: "Annualisation" method**

Based on the data presented in Table 3, the annualised investments and annual operating costs due to CCS implementation are equal to 11.71 and 36.34 M€/y. Using these numbers and the annual amount of CO_2 avoided by CCS implementation (0.579 $MtCO_2$/y), the "annualisation" method results in a CO_2 avoidance cost of 83.0 €/$t_{CO2,avoided}$.

This case evaluation confirms that the three CO_2 avoidance cost methods result in the same estimate when the necessary conditions of validity, identified in section 3, are met.

5 CONCLUSIONS

Three methods for calculation of CO_2 avoidance costs are commonly used in the literature, however users are not always aware of their conditions of validity, nor of their advantages and drawbacks. The "exhaustive" calculation method is similar to the CO_2 avoidance calculation method used in the power

†An overnight CAPEX corresponds to the total CAPEX taking also into account the effect of the capital expenditure allocation associated with construction schedule.

generation industry. This method has the strongest domain of validity but requires the complete assessment and evaluation of the industrial plant considered both with and without CCS. However, in certain cases, the assessment and evaluation of the industrial plant may not be necessary, which would reduce the effort and resources required for accurate evaluation of the CO_2 avoidance cost. The "net present value" and "annualisation" calculation methods require significantly less effort to assess and evaluate the industrial plant and can therefore be more efficient. However these approaches also come with significant limitations that are not always understood by users, and shall thus be used carefully. For example, the implementation of CCS must not impact the production of the industrial plant, which may not be applicable for certain combinations of CCS technologies and industrial plants. In view of these elements, it is therefore recommended to use Table 2 in order to ensure the selection of the CO_2 avoidance cost calculation method which is both valid and the most efficient for the cases considered by potential users.

Finally, beyond the specific cost issue considered in this work, it is also important to realise that, despite recent efforts to establish common CCS cost guidelines [19, 26], several methodological issues around cost evaluation of CCS (evaluation of low-TRL technologies [27], impact of data uncertainties [28], utilities cost [7], etc.) remain and should be further investigated.

Table 4: Summary of assumptions, advantages and drawbacks of each CO_2 avoidance cost calculation methods

Calculation method	"Exhaustive"	"Net present value"	"Annualisation"
Equation number	2	3	4
Necessary assumptions for validity			
Production of industrial plant not affected by CCS implementation	-	Yes	Yes
Additional costs and CO_2 emissions avoided due to CCS implementation can be assessed separately	-	Yes	Yes
Annual operating costs and CO_2 emissions avoided must be constant over project duration	-	-	Yes
CO_2 emissions linked to construction can be neglected or excluded	-	-	Yes
Advantage(s)/Drawback(s) of the method			
Always valid	Yes	No	No
Valid for all combinations of CCS technologies and industrial plant	Yes	No	No
Requires limited technical data concerning the industrial plant considered	No	Yes	Yes
Does no require cost estimates for the industrial plant considered	No	Yes	Yes

ACKNOWLEDGEMENTS

This publication has been produced with support from the NCCS Centre, performed under the Norwegian research program Centres for Environment-friendly Energy Research (FME). The authors acknowledge the following partners for their contributions: Aker Solutions, ANSALDO Energia, CoorsTek Membrane Sciences, Gassco, KROHNE, Larvik Shipping, Norcem, Norwegian Oil and Gas, Quad Geometrics, Shell, Statoil, TOTAL, and the Research Council of Norway (257579/E20).

The author wishes to thank Rahul Anantharaman, Amy Brunsvold, Lily Gray, Alan Reid, Stanley Santos, and Mari Voldsund for their valuable comments and discussions.

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