14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

CCUS scenarios for the cement industry: is CO_2 utilization economically feasible?

Juliana Monteiro[a*], Simon Roussanaly[b], Mari Volsund[b], Peter van Os[a], Earl Goetheer[b]

[a]*TNO, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands*
[b]*SINTEF Energy Research, Sem Sælandsvei 11, NO-7465 Trondheim, Norway*

Abstract

In this work, four illustrative CO_2 capture utilization and storage chains are investigated in order to evaluate the economic feasibility of CCUS technologies in connection to the cement industry. For that, a CCS reference case in which 90% of the CO_2 emissions (or 0,694 $MtCO_2$/y) are stored in a saline aquifer is first studied. Due to emissions related to energy usage in the capture, conditioning and transport processes, a total of 0,504 $MtCO_2$/y are avoided, or 65% of the CO_2 emitted by the cement plant at a cost of 114 €/ton CO_2 avoided.

For CCUS, we show that the economic feasibility is case dependent. In case of fuel production, the CO_2 footprint of the fuel that is displaced has a great influence on the avoidance cost: while producing blue ethanol to displace sugarcane ethanol is unfeasible, the displacement of wheat-based ethanol leads to an improved business case as compared to the reference CCS case. The cost of producing ethanol is estimated as 656 €/ton. This cost is only slightly above the market value of 633 €/ton. While the process of producing blue ethanol is not cost-competitive, it contributes to increasing the total CO_2 avoidance of the CCUS. In this way, the cost per tonne of CO_2 avoided drops from 114€ (CCS) to 111€ (sugarcane) or 96€ (wheat).

In the second scenario, we have evaluated the integrated production of polyols. This case leads to a profitable operation of the CCUS chain, because CO_2 replaces an expensive chemical as a raw material, and lowers the CO_2 emissions of the chain while doing so. The entire CCUS chain avoids 0,708 $MtCO_2$/y, and produces 288 kt/y of polyols, generating a profit of 18 €/ton CO_2 avoided. In the third scenario, we show that the production of food-grade CO_2 is feasible as long as it is used to replace fossil-derived CO_2. Setting the price of food-grade CO_2 at 80 €/t, the total CCUS avoidance cost is 108 €/ton.

A general conclusion from this work is that the average cement plant emits much more CO_2 than can be utilized in a single CCU plant. That is either due to market constrains or limited availability of raw materials. For the routes evaluated in this work, the fraction of the emitted CO_2 directed to the utilization plant was always below 10%. Therefore, when connected to the cement industry, utilization is not likely to be applied as a stand-alone solution, but as an integrated link in the CCUS chain.

Keywords: CCUS; cement industry; CO_2 utilisation; ethanol; polyols; geological storage

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* Corresponding author. Tel.: +31 88 866 46 70.
E-mail address: Juliana.monteiro@tno.nl

1. Introduction

Driven by the need to limit global warming, governments' commitment to reduce carbon footprint, and the need for value creation to support carbon capture, many novel carbon capture and utilization (CCU) technologies to convert CO_2 into fuels, minerals or value-added chemicals have been reported. In a recent roadmap, the potential of CO_2 utilization adds up to a maximum of 7 Gt of CO_2 uptake per year by 2030 [1]. As the quantity of CO_2 uptake by CCU is limited by the market, and given that the global emissions from the energy sector stood at 32,1 Gt in 2016 [2], CCU options can only be complementary to CO_2 storage, in order to achieve a significant decarbonisation through carbon capture.

The cement industry is one of the major sources of CO_2, corresponding to about 6-7% of global anthropogenic emissions. About 60% of these emissions come from mineral decomposition ($CaCO_3$ to CaO), and the remainder is from fuel combustion. CO_2 is therefore an unavoidable by-product of the process and in order to significantly reduce the climate impact of cement production, carbon capture is unavoidable. As consequence, the IEA points to CO_2 capture and storage (CCS) as the major contributor to emission reductions in the cement industry (56% by 2050, with up to 920 Mt of CO_2 stored per year) to be deployed from 2020 [3].

In the framework of the H2020 CEMCAP project [4], a reference cement plant was defined based on the best available technique standard as defined in the European BREF-Document for the manufacture of cement. This reference plant has a clinker capacity of 3000 t/d, which corresponds to a yearly cement production of 1,36 Mt per year, with a specific CO_2 emission of 625 kg/t cement [5].

The best CCUS option for each cement plant is dependent on the plant location, as the local market demands, waste heat availability within the plant, and local availability of geological storage sites, amongst other factors, will influence the economics of the CCUS chain. In order to evaluate the economic feasibility of CCUS technologies in connection to the cement industry, and to understand the interaction between utilization and storage, four illustrative CO_2 capture utilization and storage chains are evaluated in this work.

A first chain, defined as a reference case, considers CO_2 capture using an amine scrubbing system and subsequent geological storage in a deep saline aquifer (CCS). For this reference chain, it is assumed that the CO_2 is transported to a storage formation on the Dutch Continental Shelf. When combining CO_2 utilization to geological storage (CCUS), three alternative chains were evaluated: making a fuel (ethanol), a polymer feedstock (polyol), and food-grade CO_2.

The CCUS chains are represented in Fig. 1.

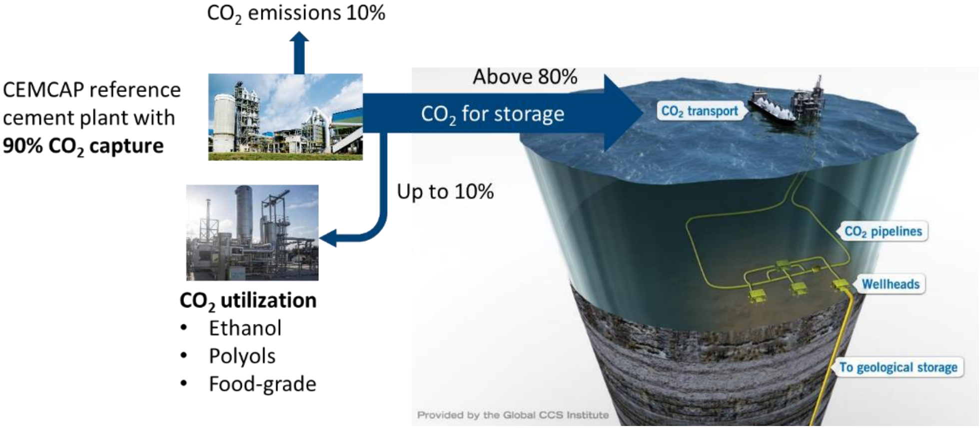

Fig. 1. Representation of CCUS chains considered in this work

Nomenclature

CO_2-eq	CO_2 equivalent
DME	dimethyl ether
MEA	monoethanolamine
Mt	million tonnes, or 10^{12} g
kt	kilo tonnes, or 10^9 g
y	year

2. Description of CCUS chains

2.1. The CCS reference chain

This chain evaluates CO_2 capture from a reference CEMCAP cement plant [6] assumed to be located in Belgium, while an offshore site on the Dutch continental shelf is considered for the storage. After capture, the CO_2 is conditioned and transported by a stand-alone pipeline to a hub in the Rotterdam area. From this hub, the CO_2 is assumed to be transported in a shared offshore pipeline to a saline aquifer. A shared transport and storage infrastructure with an annual flow of 13,1 Mt_{CO2}/y as in the EU project COCATE [7] is considered. This chain is meant to be representative of both CCS from an inland cement plant and implementation of CCS once a strategy for joint CCS transport and storage infrastructure has been established.

The CCS reference case is described in detail in Table 1.

Table 1. Description of the CCS reference chain

Section	Parameter	Value
Cement plant	Approximate location	Inland Belgium
	Capacity [Mt_{cement}/y]	1,36
	CO_2 emissions without CO_2 capture [Mt_{CO2}/y]	0,771
	Exhaust flue gas average flow [t/h]	353,15
	Exhaust flue gas average CO_2 content [mol%]	19,8
CO_2 capture and conditioning	Type of capture technology	MEA-based
	CO_2 capture ratio [%]	90
	CO_2 captured [Mt_{CO2}/y]	0,694
	Conditioning specification after capture	Pipeline
	Pressure after conditioning [bar]	150
	Temperature after conditioning [ºC]	40
First transportation step	Transport scenario	Stand-alone onshore pipeline to a Dutch hub
	CO_2 transported [Mt_{CO2}/y]	0,694
	Transport distance [km]	120
	Required pressure after reconditioning [bar]	200
Second transportation step	Transport scenario	Shared offshore pipeline to storage
	CO_2 transported [Mt_{CO2}/y]	131
	Transport distance [km]	150
	Minimum delivery pressure at storage [bar]	60

Storage	Storage type	Saline aquifer
	CO_2 stored [Mt_{CO2}/y]	13,1
	Well injectivity [Mt_{CO2}/y/well]	0,8
	Storage location	Dutch continental shelf

2.2. CCUS: integrated blue ethanol production

Ethanol obtained from CO_2 from industrial sources is referred to as *blue ethanol*, to differentiate it from *green ethanol* obtained from biomass fermentation. It should be highlighted that the differentiation is made regarding the production route, and not the quality of the final product.

The blue ethanol production route considered in the present work is based on the model presented by Astonios et al. [8]. In a first step, CO_2 is hydrogenated to methanol, which is dehydrated to DME. This is followed by DME carbonylation to methyl acetate, which is finally hydrogenated to ethanol. This technological route is currently in TRL 3 (i.e., the proof of principle is shown in laboratory environment).

The route requires renewable hydrogen to be available. For this, it is assumed that 50 MW of excess renewable electricity are available. This value represents 0,07% of the predicted 70 GW of installed wind generation capacity in the North Sea by 2030 [9]. The 50 MW can be used to produce 3,2 kt_{H2}/y (considering an efficiency of 61,6% and an availability of 40,5%), at a cost of 1,04 €/kg. This cost is obtained considering that the excess electricity is available for free, which is a very favorable scenario for hydrogenation.

The availability of renewable hydrogen greatly limits the CO_2 utilization capacity, and consequently the ethanol throughput. Via the conversion of 23,8 kt_{CO2}/y, or 3,1% of the emissions of the CEMCAP plant, 12,5 kt/y of ethanol are produced. As 90% of the CO_2 emissions are captured, the non-utilized fraction (86,9%) are assumed to be directed to the storage site. Therefore, the proposed utilization route is not a stand-alone solution, but works as an integrated link in a CCUS chain.

2.3. CCUS: integrated polyol production

Propylene oxide (PO) is the main feedstock in industrial polyol manufacturing routes. A novel route, in which PO is partially replaced by CO_2 has been proposed [10]. The CO_2 content in the polyol product is set to 20 wt%. This novel route is evaluated in the current work.

The typical size of polyols plants is around 100 kt/y, whereas the polyols market is around 10 Mt/y. Based on these market numbers, the polyol throughput is set at 288 kt/y. The CO_2 utilization capacity is therefore limited by the throughput of the polyol plant, which in its turn is limited by the market. The simulated polyol plant consumes 57,5 kt_{CO2}/y, which is equivalent to 7,5% of the emissions of the CEMCAP reference plant. Therefore, 82,5% of the CO_2 emitted needs to be stored. Again, given the mismatch of scales between the cement and the CCU plant, utilization cannot be applied as a stand-alone solution, but as an integrated link in a CCUS chain.

2.4. CCUS: integrated food-grade CO_2 production

Food-grade CO_2 can be used inside greenhouses to raise the atmospheric CO_2 levels to 600-1000 ppmw, in order to accelerate the plants growth. In The Netherlands, during the summer, natural gas is combusted on a large scale to provide CO_2 to greenhouses, leading to net emissions of about 7 Mt_{CO2}/y. An annual growth of 100 kt_{CO2}/y in the Dutch CO_2 market is expected up to 2020. Additionally, the food and beverage industries consume about 17 Mt_{CO2}/y worldwide [11].

The conceptual design of a plant for purifying CO_2 to food-grade quality and liquefying it are developed. The plant capacity is set as 50 kt_{CO2} per year or about 6,5% of the emitted CO_2. It is considered that the plant will serve endusers which are currently producing their own CO_2 locally. Burning natural gas to generate CO_2 is still a common practice in the horticulture industry in The Netherlands. Therefore, blue CO_2 directly replaces fossil-derived CO_2.

3. Results

3.1. CCS results

As shown in Table 1, the CO_2 capture rate is set as 90%, or 0,694 Mt_{CO2}/y. However, due to emissions related to energy usage in the capture, conditioning and transport processes, the amount of CO_2 avoided is lower than that. The quantity of CO_2 avoided is determined by the difference between the quantity of CO_2 captured and the emissions associated to each one of the processes of the chain. In the CCS reference case, 0,504 Mt_{CO2}/y are avoided, or 65% of the CO_2 emitted by the cement plant. The total cost of CO_2 avoided is 114 €/ton.

3.2. CCUS results: ethanol production

The cost of producing ethanol via DME is estimated as 656 €/ton of ethanol, based on the work of Atsonios [8]. This cost is only slightly above the market value of 633 €/ton. Hydrogen, even at an extremely low cost, represents 41% of this total.

The calorific value of ethanol is 29,7 GJ/ton. In terms of energy, the ethanol production cost is 22 €/GJ. In the cement plant, coal is used as fuel, and has the price of 3 €/GJ. Therefore, substituting coal by ethanol would lead to a weaker business case. From that perspective, the produced ethanol should be sold on the market where it could substitute fuels with higher quality than coal – for instance, green ethanol.

Currently, the most cost- and CO_2-effective process for the production of green ethanol is the fermentation of sugarcane. While sugarcane growth fixates CO_2 from the atmosphere, the various steps in the production of green ethanol emit CO_2, and the net result is the emission of 3,3 t_{CO2}/ton green ethanol. In case of ethanol production from wheat, the efficiency is lower, and the emissions are 3 times higher. In the current case, 12,5 kt/y of blue ethanol are produced, thus replacing the same flow of green ethanol. This replacement leads to the avoidance of 41 and 123 kt of CO_2 per year, using sugarcane and wheat as raw material, respectively.

While the process of producing blue ethanol is not profitable, it contributes to increasing the total CO_2 avoidance of the CCUS chain to 0,518 Mt_{CO2}/y (67% of the cement plant emissions) in the sugarcane case and 0,6 Mt_{CO2}/y in the wheat case, as compared to 0,504 Mt_{CO2}/y of the reference CCS case. In this way, the cost per tonne of CO_2 avoided drops from 114€ (CCS) to 111€ (sugarcane) or 96€ (wheat). The cost difference for sugarcane is only marginal, but in the case of wheat, it appears more relevant. It should be noted, however, that these cost differences are within the expected uncertainty level for the estimate procedure (at best, +/- 30%).

This CCUS chain demonstrates the complexity involved in the CO_2 avoidance cost analysis: it must take into consideration not only the product that is formed, but also the market in which it is placed. The economic feasibility of integrating ethanol production to a CCS chain is therefore case dependent, and the economic evaluation must be supported by a life cycle assessment analysis.

3.3. CCUS results: polyols production

The polyol plant CAPEX is estimated to be 21 M€, taking the work of by Fernández-Dacosta [10] as basis. Regarding the price of chemicals, a conservative approach is used, as both polyol and PO prices are set as 1400 €/t (zero spread). The business case of blue polyol production lies partially on the fact that the CO_2 content in the material is replacing PO. The gate cost of CO_2 after capture is 69 €/t, much lower than that of PO. Therefore, the production costs are greatly reduced.

The production of PO is carbon-intensive: 4,5 $t_{CO2\text{-}eq}$ are emitted per ton of PO produced. Therefore, even with the partial substitution of PO by CO_2, the polyol production process is still a net CO_2 emitter if the CO_2 content in polyol is limited to 20wt%. The route becomes a net CO_2 consumer when at least 50% of the PO is substituted by CO_2 – which is unfortunately not yet technically feasible, as it leads to low quality polymers. Yet, the production of blue polyol avoids the emission of 0,91 $t_{CO2\text{-}eq}$ per ton of PO as compared to the conventional route.

The entire CCUS chain avoids 0,708 Mt_{CO2}/y, and produces 288 kt/y of polyols. Due to the high value of polyols, the full chain is profitable. Even when setting the spread between the polyol and the PO prices to zero, the profit is of 43 €/ton of polyol produced, or 18 €/ton CO_2 avoided.

3.4. CCUS results: food-grade CO_2 production

Because the direct avoidance of fossil CO_2 cancels out the emissions of food-grade CO_2, the total CO_2 avoidance of this CCUS case is the same as that of the reference CCS: 0,504 $MtCO_2$/year or 65% of the cement plant emissions.

The price of food-grade CO_2 is highly dependent on the location, but for Europe it can be around 80-150 €/ton. In the Netherlands, CO_2 delivered via a distribution pipeline to vegetable growers has a market cost of between €50-80 per ton CO_2, depending on transportation distance and greenhouse capacity [11].

Setting the price of food-grade CO_2 at 80 €/t, the total CCUS avoidance cost drops 5%, from 114 to 108 €/ton. The break-even CO_2 price – that leads to the same avoidance cost for CCUS and CCS – is 25€/t, thus below the current European price range. From this perspective, producing as much food-grade CO_2 as can be placed in the market is a viable option for lowering the integrated CCUS costs.

However, if green CO_2 is available (e.g. from fermentation), the CCUS option actually leads to a higher cost than CCS: 120 €/ton CO_2 avoided, for a CO_2 market price of 80 €/ton. In this case, the substitution of green CO_2 by blue CO_2 leads to lower CO_2 avoidance by the full chain – or lower sequestration efficiency – which has a detrimental effect on the avoidance cost.

4. Conclusions

Already in the title of this paper we have posed a question regarding the economic feasibility of integrating CO_2 utilization to CCS chains in the cement industry. By evaluating the CCUS chains proposed, the answer to that is: it depends. We show, for the fuel case, that the characteristics of the product that is displaced has a great influence on the avoidance cost: while producing blue ethanol to displace sugarcane ethanol seems unfeasible, the displacement of wheat-based ethanol leads to an improved business case as compared to the reference CCS chain. It should be highlighted that these results consider the use of free excess electricity, which is an optimistic scenario.

In the second CCUS chain, we have evaluated the integrated production of polyols. This case leads to a profitable operation, because CO_2 replaces an expensive chemical as a raw material, and lowers the CO_2 emissions of the chain while doing so. While the polyols market is limited as compared to the total amount of CO_2 to be avoided by the cement industry as a whole, this CCUS case could be feasible for some cement plants. Moreover, the polyols case may be representative of other high added value products, such as other polymer precursors or cyclic carbonates.

In the third CCUS chain, we show that the production of food-grade CO_2 is feasible as long as it is used to replace fossil-derived CO_2 produced especially to be used in the food and beverage industries or in greenhouses. If CO_2 from other sources is available – such as green CO_2 from fermentation, then this CCUS scenario leads to higher CO_2 avoidance costs.

A general conclusion from this work is that the average cement plant emits much more CO_2 than can be utilized in a single CCU plant. That may be due to market constrains, as in the cases of polyols and food-grade CO_2, or low availability of raw materials, as in the case of ethanol and fuels in general (which require renewable hydrogen). For the routes evaluated in this work, the fraction of the emitted CO_2 directed to the utilization plant was always below 10%. Therefore, when connected to the cement industry, utilization is not likely to be applied as a stand-alone solution, but as an integrated link in the CCUS chain.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 641185 (CEMCAP).

References

[1] CO2 Sciences and The Global CO2 Initiative, "Global Roadmap for Implementing CO2 Utilization," 2016.

[2] IEA, "IEA finds CO2 emissions flat for third straight year even as global economy grew in 2016," *International Energy Agency*, 2017.

[3] WBCSD and IEA, "Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050," p. 36, 2009.

[4] CEMCAP, "H2020 Project ID: 641185 - CO2 capture from cement production." .

[5] R. Anantharaman *et al.*, "D3.2 CEMCAP framework for comparative techno-economic analysis of CO2 capture from cement plants," 2017.

[6] S. Roussanaly, C. Fu, M. Voldsund, R. Anantharaman, M. Spinelli, and M. Romano, "Techno-economic Analysis of MEA CO2 Capture from a Cement Kiln – Impact of Steam Supply Scenario," *Energy Procedia*, vol. 114, pp. 6229–6239, 2017.

[7] P. Coussy, S. Roussanaly, G. Bureau–Cauchois, and T. Wildenborg, "Economic CO2 network optimization model COCATE European Project (2010-2013)," *Energy Procedia*, vol. 37, pp. 2923–2931, 2013.

[8] K. Atsonios, K. D. Panopoulos, and E. Kakaras, "Thermocatalytic CO2 hydrogenation for methanol and ethanol production: Process improvements," *Int. J. Hydrogen Energy*, vol. 41, no. 2, pp. 792–806, 2016.

[9] VoltaChem, "Port of Rotterdam sees opportunities for power to hydrogen," 2017. [Online]. Available: http://www.voltachem.com/news/port-of-rotterdam-sees-opportunities-for-power-to-hydrogen. [Accessed: 25-Oct-2017].

[10] C. Fernández-Dacosta *et al.*, "Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO2 utilisation in polyol synthesis," *J. CO2 Util.*, vol. 21, no. Supplement C, pp. 405–422, 2017.

[11] T. Mikunda, F. Neele, F. Wilschut, and M. Hanegraaf, "A secure and affordable CO2 supply for the Dutch greenhouse sector," 2015.