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THE COSTS OF CO_2 CARBONATION IN THE CEMENT INDUSTRY

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Abstract

Rising climate change requires rapid changes in high emitting industries such as the cement industry. A concept developed in recent years which attracts researchers, entrepreneurs and policy makers alike is the so-called Carbon Capture and Utilisation (CCU). A major hurdle for implementing CCU technologies is often their economic viability. A process of particular interest for cement producers in the field of CCU are the so-called CO_2 carbonation processes, where CO_2 reacts with minerals to form stable carbonates. We assessed the main direct carbonation routes showing that Supplementary Cementitious Materials produced via CO_2 carbonation (SCM_{CCU}) could be produced at scale with Levelised Cost of Product of 120€/t_{SCM} which lies in the range of current selling prices of cement. Hence, using SCM_{CCU} could potentially become an economically viable way of reducing emission in this sector.

Keywords: *Techno-economic assessment, CO_2 carbonation, cement*

1. Introduction

Climate change poses a threat to life on earth as humans know it, and possibly even humanity itself. Anthropogenic emissions of greenhouse gases have been identified as a major cause for this effect. Among these is the molecule CO_2, which is commonly emitted through combustion of fossil fuels such as oil.[1] In order to tackle climate change, a majority of the countries in the world decided to reduce their CO_2 emissions in the upcoming years and decades with the Paris agreement in 2015.[2] Because approximately 30% of the anthropogenic CO_2 emissions are bound to industrial processes, with the largest emitting sectors being the steel and cement industry, a rapid change is needed to fulfil the emission reduction goals in this division.[1]

A concept developed in recent years, which could possibly procure CO_2 emission reductions for many sectors is the so-called "Carbon Capture and Utilisation" (CCU). It has become a model which attracts researchers, policy makers and entrepreneurs in search of climate change mitigation solutions. The general idea is not to emit CO_2 directly, but to use the produced CO_2 to create products from it. Usually this concept is demarcated from the concept "Carbon Capture and Sequestration" (CCS), where CO_2 is (geologically) stored and no product is formed. At the end of their lifetime, many CCU products can be incinerated and the resulting CO_2 can be circled back again[3]. The concept is depicted in Figure 1. CCU can possibly play a large role in the de-fossilization of certain industry sectors and foster the development towards circularity in industrial processes.

It has been argued that a main advantage of the CCU concept is that industry does not need to completely change all existing processes, but it can rather be a supplement to current production routes, which makes the transition to an environmentally sustainable society faster and more likely. Additionally, in particular instances, it might be possible to gain economic profit from it.[3]

A major hurdle for implementing CCU technologies is often their economic viability. Therefore, economic assessments of these technologies are of major importance for decision-makers in industry and politics, but also for upcoming entrepreneurs.[4]

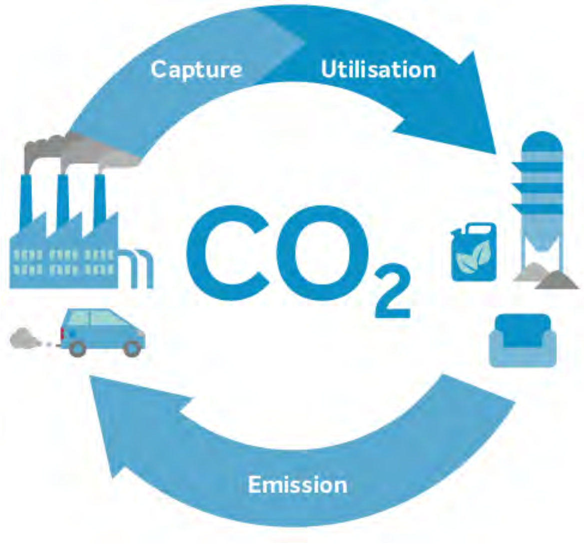

Figure 1: The economic carbon cycle taken from Zimmermann et al.[3]

Being among the biggest emitters of anthropogenic CO_2, the cement industry in particular requires rapid solutions in order to foster a development towards a sustainable future.[5] A closer look at the processes reveals that roughly 60% of the cement industries emissions are process-inherent emissions and are emitted via the calcination of limestone and therefore they are not energy related and need a distinctive mitigation approach.[6,20] As long as the same reactions and feedstocks are used process-inherent emissions will still occur. Hence, solutions such as electrification of the process which only tackle energy related emissions and do not alter process-inherent emissions, will not be sufficient to reach net zero emissions in the cement industry. Hereby, CCU technologies could potentially be a part of the solution.[5] A technological concept developed in this field is CO_2 carbonation often also referred to as CO_2 mineralisation. CO_2 is reacted with activated minerals to form stable carbonates.[7,8] While many CCU products offer limited CO_2 storage potential since stored CO_2 might be released at the end of their life cycle, carbonates are a mean to store CO_2 permanently. The global storage potential of CO_2 carbonation has been estimated to be at least 10 000Gt carbon due to an abundance of mineral feedstock.[8,9] Carbonation products could potentially be used for multiple purposes, such as fillers, Supplementary Cementitious Materials (SCM) or for land reclamation projects.[9,10,11,12]

The concept of CO_2 carbonation is not new to the sustainability community. It has been researched as a storage solution for CO_2 (CCS) in recent years without focusing on the formation of a product, which can possibly create additional revenue for the emitter of CO_2 and potentially substitute carbon intensive products such as cement.[8]

Some policy advise reports[13] use CO_2 carbonation process as a positive example for using CO_2 as a feedstock, because unlike most other CO_2 utilisation concepts, the mineralisation reaction is energetically favored.[14] Controversially, a literature review revealed the lack of detailed economic assessments for these processes as a CCU technology. Additionally, it was found that when economic assessments are performed in this field they are habitually not comparable, due to the use of different assumptions and often an economic evaluation is solely done on the basis of energy consumption.[8,9,15] Energy consumption itself might be a major driver for the operational costs using a CCU technology, but research has shown that investment decisions are not always bound to this criteria.[16] Therefore, a systematic comparison of multiple mineralisation pathways is needed to provide decision-makers with the information necessary to verify the feasibility of successfully implementing such technologies. Moreover, a detailed assessment can also be used for additional purposes, such as evaluating under which circumstances a novel technology becomes economically feasible and to detect key factors which can be influenced in order to reach economic feasibility. It is also crucial to investigate additional factors that can influence whether a technology will be deployed.

This contribution aims to uncover the costs of different proposed CO_2 carbonation routes as well as their scaling effects through a rigorous techno-economic assessment (TEA).

2. Carbonation processes

In literature direct aqueous carbonation reactions have been extensively studied.[8,15,17,18,19] Magnesium or calcium-rich rocks such as olivine or serpentine have been proposed as feedstocks for the carbonation reaction.[15,19] The general reaction can be described as follows in which M represents MgO and CaO:

$$MO + CO_2 \rightarrow MCO_3 + heat \qquad \text{Eq. 1}$$

In proposed direct aqueous carbonation routes captured CO_2 is reacted in an autoclave using increased pressure and temperature in an aqueous slurry reaction. To counteract slow reaction kinetics rocks a mechanically or thermally activated (grinding and calcination) and additives such as NaCl, or $NaHCO_3$ are added.[15,19]

When silicate rich feedstocks such as olivine or serpentine are used for the carbonation the by-product silica (SiO_2) is obtained, which is often a part of many Supplementary Cementitious Materials such as steel slag used in cement blends today. Hence, it is foreseen that carbonation products can be used as SCMs in the cement industry.[11,12,20]

3. Methods

Unlike life cycle assessment (LCA), techno-economic assessments do not follow an ISO standard resulting in less homogeneous results among published studies. For this study recently published guidelines[4] as well as the proposed methodology by Rubin et al.[21,22] were followed. This process begins with the scope definition.

2.1 Scope of the assessment

The process can be distinguished by multiple process units, which have to be included into the scope of the assessment (see Figure 2). We choose ton of cement replacement produced (hereafter referred to as Supplementary Cementitious Material from CCU, short SCM_{CCU}) as the functional unit. We define the SCM as 40% SiO_2 and 60% $MgCO_3$. Gravity separation in the post-treatment is used to obtain this composition.[23]

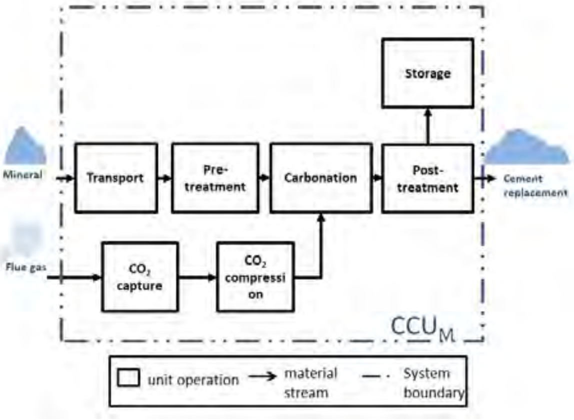

Figure 2: System boundaries for the assessment of carbon capture and utilisation through the means of mineralisation (CCU_M). Adapted from Ostovari et al.[20].

2.1 Calculating the costs of CO_2 carbonation

The indicator chosen for this assessment is Levelised Cost of Product (LCOP) per ton of SCM_{CCU} produced. This incorporates both capital (CapEx) and operational (OpEx) expenditures needed to produce the carbonated product. The capital costs are discounted using the interest rate and the lifetime of the plant to evaluate the true cost of capital for the proposed plants (see Eq. 2 and Eq. 3).

$$LCOP = \alpha \cdot CapEx + OpEx \qquad \text{Eq. 2}$$

$$\alpha = \left(\frac{i}{1-(1+i)^{-L}}\right) \qquad \text{Eq. 3}$$

We calculate the CapEx using the Total Plan Cost (TPC) and Total Direct Costs (TDC) (see Eq. 4).

$$TPC = \sum TDC \cdot (1 + f_{indirect}) \cdot \left(1 + f_{process}\right) \cdot \left(1 + f_{project}\right) \cdot (1 + f_{owner}) \qquad \text{Eq. 4}$$

Here, $f_{indirect}$, $f_{process}$, $f_{project}$, f_{owner} represent indirect costs, process contingencies, project contingences and owners costs.

To derive the TDC for each process unit we use both a bottom-up approach for all process units of which costs have not been widely studied (i.e. carbonation reactor) as well as a top down approach for units that have been studied thoroughly in literature. The top down approach is used for the CO_2 capture (monoethanolamine (MEA) post combustion capture) as well as the CO_2 compression. Here, published estimations by Voldsund et al.[24] (CO_2 capture) and Van der Spek et al.[25] (CO_2 compression) are used. The top down approach is shown in Eq. 5.

$$TDC_{top\,down} = TDC_{old} \cdot \left(\frac{\dot{m}_{new}}{\dot{m}_{old}}\right)^{n} \cdot \left(\frac{I_{new}}{I_{old}}\right) \qquad \text{Eq. 5}$$

The plant capacity is used by $\dot{m}_i$ in [t/a]. n represents the scaling factor and I capital cost index for a certain year to account for inflation. Here, the chemical Engineering Plant Cost Index (CEPCI)[26] is used. For all other process units, a bottom up approach is used to derive TDC. In the bottom up approach Aspen Capital Cost estimator is used to derive estimations of the TDC of each unit directly.

The overall CapEx are derived incorporating learning effects following Rubin et al.[21,22] (see Eq. 6 and Eq. 7).

$$CapEx = \left(\frac{TPC}{\dot{m}_{SCM}}\right) \cdot N^{-E} \cdot \dot{m}_{SCM} \cdot (1+i)^{t_{construction}} \qquad \text{Eq. 6}$$

$$E = \frac{\ln(1-LR)}{\ln(2)} \qquad \text{Eq. 7}$$

N characterizes the number of plants necessary, LR the learning rate, *E* the experience factor, *i* the interest during construction and $t_{construction}$ the estimated time for construction.

The operational expenditures are derived using mass and energy balances for the costs of utilities and feedstocks, the costs of material transport and the costs of labour (see Eq. 8).

$$OpEx = \sum w_i \cdot \pi_i + \dot{m}_{mineral,in} \cdot \sum \pi_j \cdot d_j + OpEx_{fixed} \qquad \text{Eq. 8}$$

The amount of feedstock or utility needed is represented by w_i, π_i is the price for feedstock or utility π_j is the price of transportation mean (i.e. truck, train or ship) and d_j the distance for material transported. The fixed operational expenditures $OpEx_{fixed}$ consist of cost for labor, insurance and local tax, maintenance and administration and support. The following assumptions are used for the calculations (see Table 1 to Table 4):

Table 1: Process assumptions

Description	Serpentine 37µm (X= 0.6)[15]	Olivine 37µm (X= 0.3)[15]	Olivine 37µm (X= 0.5)[15]	Olivine 10µm (X= 0.6)[19]	Olivine 10µm (X= 0.8)[19]
Yield	0.6	0.3	0.5	0.6	0.8
particle size [µm]	37	37	37	10	10
P [bar]	115	150	150	100	100
T [°C]	155	185	185	190	190
c_{NaHCO3} [mol/l]	0.64	0.64	0.64	0.5	0.5
c_{NaCl} [mol/l]	1	1	1	0.75	0.75

Table 2: Economic Assumptions: *median of multiple values used.

Variable	Value	Reference
Working hours	8000h/year	Deolalkar[27]
Lifetime	30 years	Own estimation
Overall interest* (including interest on equity and dept)	7.69%	European Central Bank[28], Gurufocus[29], Macrotrends[30,31]
Extraction Costs Mineral*	12€/t	Brown, et al.[32]
Transport distance (1000km)	60km truck 200km train 740km ship	Ostovari, et al.[20], own estimation
Transport costs	0.04€/tkm truck 0.032€/tkm train 0.0032€/tkm ship	Brown, et al.[32]
Electricity price*	62€/MWh	European Commission [33]
Natural gas price*	32€/MWh	Duić, et al. [34]
Price $NaHCO_3$*	209€/t	Comparison of vendor prices[35]
Price NaCl*	61.6€/t	Comparison of vendor prices[35]
Price MEA*	1320€/t	Comparison of vendor prices[35]

Table 3: Factors used for CapEx calculation.

Description	Value	Reference
Indirect costs	14%	Anantharaman et al.[36]
Process contingencies	40%	EPRI[37], AACE[38]
Project contingencies	30%	EPRI[37]
Owner's costs	7%	Grande et al.[39]
Learning rate	10.5%	Rubin et al.[40]
Number of plants	20	Greig et al.[41]

Table 4: Factors used for OpEx calculation

Description	Value	Reference
Insurance and local tax	2% of TPC	Anantharaman et al.[36]
Maintenance	2.5% of TPC	Anantharaman et al.[36]
Administration and support	30% of operating and maintenance	Anantharaman et al.[36]

3. Results

The results are shown in Figure 3. Overall, the results indicate that cost reductions due to size (economies of scale) are most significant for plant sizes up to roughly 15-20kt/a. Surpassing this size building a bigger plant will only lead to minor production cost reductions. Additionally, the suggested process routes show a difference in calculated production costs of roughly 50€/t of SCM$_{CCU}$, which translates to a 40% increase from lowes costs to highest costs.

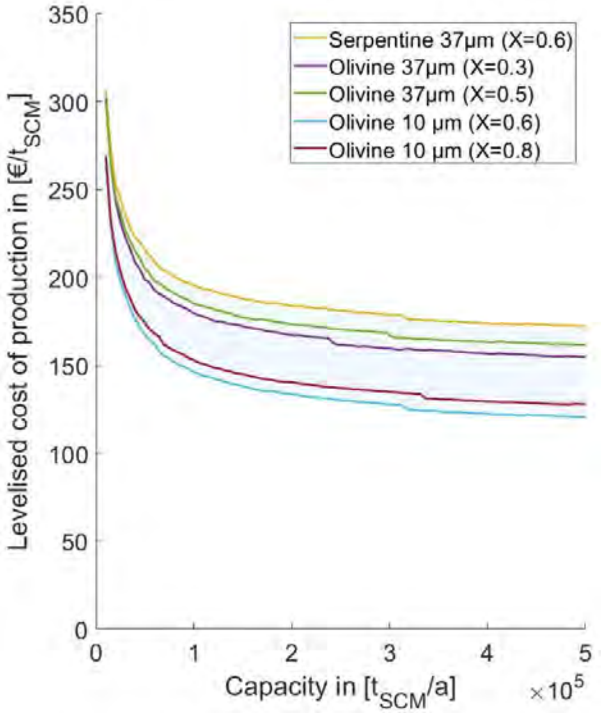

Figure 3: Levelised Cost of Product for SCM$_{CCU}$

The process proposed by Eikeland et al.[19] shows the lowest costs with a LCOP of 120€/t_{SCM} at a capacity of 500kt$_{SCM}$/a. Here, olivine is used as a feedstock wich is grinded to 10µm. Hence, higher operational costs due to higher energy demand for grinding as well as increased CapEx for grinding mills are off-setted by the lowered cost due to higher reaction extends compared to processes where 37µm grinding is proposed. Additionally it is shown that overall a yield of 0.6 appears to be lower in costs for producting a SCM with the same propoerties, compared to a yield of 0.8 for the same reaction conditions (see Figure 3, Olivine 10µm (0.6) and Olivine 10µm (0.8)).

4. Conclusion

Emission reduction in high emission sectors often comes with additional costs. The results show that large CO_2 carbonation plants might be economically feasible. With cement prices in Europe ranging from 70 to 150€/t_{cement}[42], the calculated prices appear to be in a competitive price range, suggesting that emission reductions could become economically feasible through the means of CO_2 carbonation. Although, studies showed that using direct carbonation can reduce the emission of cement production significantly when applied in the large scale[20] further assessments should be performed analysing differences in costs and emissions for selected SCM product specifications (i.e. SiO_2 contents). The final costs of the system can be determined, when product specifications are set for SCM via CCU.

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