USING THE URBAN STOCK AS A CARBON SINK: A CASE STUDY FROM THE GERMAN FEDERAL STATE OF NORTH RHINE – WESTPHALIA

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Abstract

The decarbonization of the industrial sector will not be feasible without carbon capture and utilization (CCU) or storage (CCS) due to unavoidable process emissions. Due to the lack of geological storage in Germany, the low social acceptance and the legal challenges, CO_2 utilization has become a favorable route to sequester the process emissions.

This paper presents a case study from North Rheine – Westphalia (NRW) in order to highlight the importance of using the urban stock (e.g. construction and demolition waste & concrete products) as a carbon sink for process emissions by means of carbonation, quantify the amounts of emissions that can be permanently stored, and illustrate the significance of the locational aspects that will affect the prospective supply chain. The analyses show that the average distance between the selected carbon sources and sinks is 55.6 Km, nevertheless, some plants have a comparative advantage in terms of the average transportation costs, which range between 2 and 31.6 EUR/ton for the shortest and longest distance respectively (8.8 Km and 142.3 Km).

Keywords: *Carbon Capture and Utilization (CCU), Urban stock, Process emissions, Carbon sink*

1. Introduction

1.1 Industrial process emissions

The German national strategy of energy transition (Energiewende) aims at achieving carbon neutrality by 2050 [1, 2, 3] There are various roadmaps aiming at investigating the potentials of using decarbonization enablers (e.g. electrification and hydrogen) in the industrial sector. Nevertheless, decarbonizing the industrial sector still represents a major challenge, not only due to the heterogeneity of the industrial processes and the risk of carbon leakage, but also due to the significant amounts of process emissions that cannot be avoided even if the fuel and energy emissions are decarbonized. In 2018, the process emissions represented 8% of the total German GHG-emissions (65 Mt CO_2 eq.) [4].

Four major industries are responsible for more than 70% of the process emissions in Germany; namely steel, cement, lime and basic chemicals [4]. The introduction of hydrogen and electrification technologies will play a vital role in decreasing the gross and process emissions of steel and chemicals. However, the specific process emissions per ton of clinker and lime (clinker = 60% & lime = 69% of the total emissions [5]) cannot be reduced by such technologies [5] as they are chemically associated with the production process (calcination) (i.e. the chemical reaction of transforming calcium carbonates into calcium oxides as shown in the following equation).

$$CaCO_3 + \text{Energy} \rightarrow CaO + CO_2$$

The case study discussed in this paper focuses on NRW as an important industrial hub in Germany with unique locational characteristics that qualify it as an appropriate region to be investigated.

Currently, CO_2 pipelines that would allow to transport CO_2 emissions to ports from where they could be shipped to be stored (Carbon Capture and Storage – CCS) are controversially discussed. Even if a pipeline network exists, it wouldn't be able to cover all locations in NRW. Many plants of the iron and steel industry are located close to waterways and thus would be able to ship their emissions easily. In contrast, cement and lime plants are located near the raw materials (limestone), which is far away from the industrial clusters in the Ruhrgebiet as shown in Figure 1. Against this background, this paper focuses on options for cement and lime plants to utilize their process emissions (Carbon Capture and Utilization – CCU).

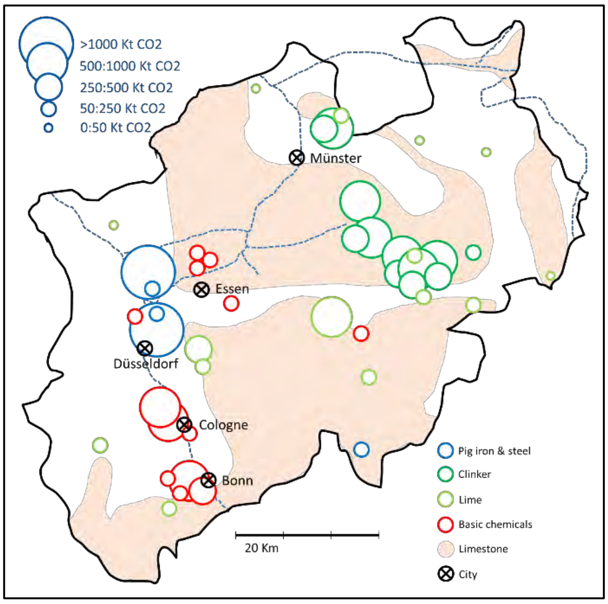

Figure 1: GHG emissions per annum of some industrial sectors in NRW, visualized based on [6, 7, 8]

1.2 Carbonation

Carbonation refers to the CO_2 reaction with oxides that results in forming stable and insoluble compounds (carbonates) as the reverse reaction of calcination. The reaction is exothermic and occurs naturally which is known as "silicate weathering" phenomena. However, the natural reaction rate is very slow as it depends on the silicate dissolution [9, 10].

$$M^{+}O + CO_2 \rightarrow M^{+}CO_3$$

Stimulated by the endeavors to find suitable routes to reduce the GHGs, various studies have been implemented in the recent years in order to utilize the primary and secondary raw materials as a carbon sink.
Some natural minerals can be used for carbonation such as Olivine, Serpentine and Wollastonite as shown in the following reactions [11]. Despite the proven technical feasibility, the amounts needed, geographical availability and logistical complexities associated make it unsecured supply chains [12].

$$Mg_2SiO_4 + CO2 \rightarrow 2MgCO_3 + SiO_2 + \text{energy}$$

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 2MgCO_3 + 2SiO_2 + H_2O + \text{energy}$$

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2 + \text{energy}$$

Cement hydration results in a set of compounds such as portlandite, CSH, CAH and other compounds. The reaction of these compounds with CO_2 dissolved in water results in stable compounds (calcium carbonate/ $CaCO_3$) as shown in the following equations [13, 14]. The carbonation of cementitious materials happens naturally during the lifetime of the construction object as an ageing effect, but it is also too slow and has a limited capacity which is known as **"passive carbonation"**.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

$$3CaO.2SiO2.3H2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO2 + 3H_2O$$

$$4CaO.Al_2O_3.13H_2O + 4CO_2 \rightarrow 4CaCO_3 + 2Al(OH)_3 + 10H_2O$$

"Active carbonation" of cementitious materials utilize these reactions for specific technical, economic and ecological purposes (i.e. carbon sequestration) [15]. Hence, construction and demolition waste (CDW) and concrete products are promising carbon sinks and have various advantages in comparison to natural minerals such as avoided mining, continuous supply and domestic availability. Moreover, compared to other CCU pathways, concrete carbonation is characterized by low energy input and sometimes, even savings in energy and CO_2 emissions result as the conventional precast curing processes is avoided [16]. Also, in contrast to geological storage, carbonation does not require high CO_2 specifications. Geological storage normally requires very low amounts of impurities due to the associated risks such as leaks, rock erosion, mineral dissolution in saline aquifers and pipeline corrosion. Strict requirements imply higher costs due to additional purification and analysis operations [17, 18]. Hence, avoiding these phases in the carbonation process would make the technology more cost-efficient.

When designing a prospective carbonation supply chain, the quantities and locations of CDW and of concrete & precast products as well as the amount of CO_2 emissions will be the most important factors. Low transportation costs and sustainable supply will provide a comparative advantage to compensate for the investments needed to retrofit the plants and to install carbonation chambers.

Due to the novelty of the technology, the majority of investigations focus on the technical feasibility and are mostly applied on a lab scale as could be seen in different research projects such as [19, 20, 21]. According to our best knowledge, no systematic analyses have been implemented to analyze the regional resources and potentials as presented in this paper.

The specific sequestration capacity is a controversial point as each study has different curing conditions (e.g. curing duration, CO_2 pressure, temperature, etc.). As a result, the amount of CO_2 that can be stored per kilogram of cement ranges between 63 and 350 gram [22, 14, 19, 23, 24]. Similarly, there is no consensus on the technology readiness level (TRL). While some studies classify the maturity of the technology as moderate such as [25], others grade it as high [21]. Nonetheless, there is consensus on the large future potential. Some optimistic views project that between 16.3% to 41.3% of the global concrete production can be used for carbonation by 2030 [26]. Some companies have already existing products and carbonation technologies such as Solidia and CarbonCure [27, 28, 29].

A clear distinction is to be made between different types of concrete products as this has various implications in terms of TRL and hence the expected market penetration rate. First, products can be classified into reinforced and non-reinforced products as the carbonation process results in a low pH that can lead to steel corrosion and hence affect the durability. Nonetheless, some experts expect that this hurdle can be overcome in the coming years [25]. Secondly, products can be classified into ready-mix concrete (RMC) and precast products due to the different manufacturing operations and product features that will affect the carbonation process, technical limits and economies.

In contrast to the concrete and precast products, CDW carbonation does not face technical restrictions like the risk of durability and steel corrosion. Moreover, it does not need high CO_2 purity, some technical reports even emphasize that the carbonation process can take place by directly using cement flue gas with a high CO_2 concentration (>20%) [21]. This can actually be a game changer as it will significantly reduce the carbon sequestration costs. Considering that the capturing process contributes significantly to the total sequestration cost [30, 31], saving these costs will help in boosting the carbonation technology. Similar to concrete carbonation, some major companies already started to invest in CDW carbonation technology such as [32, 33, 34, 35].

Nevertheless, a robust CDW recycling system and enhancing policies are a precondition for establishing a carbonation supply chain. Within an established and efficient CDW recycling system, carbonation could even be a valorization. If these prerequisites are missing, the costs of using the secondary materials as carbon sink, i.e., the sum of collection, transportation and processing costs, would be much higher. In the following, we will analyze the conditions in terms of spatial characteristics and resources for NRW. Table 1 summarizes the key carbonation performance data used in the following sections.

Performance	Value	Reference
Cement content in concrete (concrete, precast and recycled aggregates)	11%[1]	[36, 37]
Carbonation (ton CO_2/ton cement) (concrete, precast and recycled aggregates)	0.35	[23, 24]
Waste cement/waste concrete (ton/ton)	0.17	[14, 38]
Concrete content in recycled rubble (ton/ton)	0.51	[39, 40]
Bricks content in recycled rubble (ton/ton)	0.1	[39, 40]
Mixed waste content in recycled rubble (ton/ton)	0.39	[39, 40]
Carbonation (ton CO_2/ton waste cement)	0.27	[41, 14]
Carbonation product 1 (ton limestone/ton waste cement)	0.61	[42, 41, 23]
Carbonation product 2 (ton residue/ton waste cement)	0.66	[42, 41, 23]
No. of cement plants	12	[6]
No. of lime plants	14	[6]
No. of carbon sinks (districts)	53	[43]
Transportation cost (Long Heavier Vehicles LHV) (EUR/ton.Km)	0.095	[44]
Transportation cost (Tractor + trailers) (EUR/ton.Km)	0.127	[44]
Average transportation cost (EUR/ton.Km)	0.111	[44]

Table1: Key carbonation performance data

1.3 Construction activities & demolition waste in NRW

NRW is the most populous and densely populated state in Germany. Hence it has a strong and dynamic construction sector especially close to the industrial cities and urban centers adjacent to the Rheine river such as Cologne, Bonn, and Düsseldorf, Duisburg and Essen (Figure 2 and 3). The non-residential sector has been stable since the eighties with an average of 4.7 million m^2 constructed per year. On the other hand, the residential sector has witnessed a boom in the nineties but stabilized afterwards with an average of 42 thousand apartments constructed per year in the last decade (Figure 4).

In terms of the raw materials and intermediate products, the state produces 9.7 Mt of cement, of which 6.3 Mt are consumed domestically to produce 8.8 million cubic meters or 21.1 Mt of RMC, 8.6 Mt of precast concrete and 1.5 Mt of other products in dry format (e.g. mortar) [45, 39]. The total cement consumption is split almost equally to three main sectors; non-residential construction = 34%, residential construction = 33% and infrastructure = 33% [46].

In terms of the demolition activities, every year, around 4,000 houses are demolished in NRW. Together with the demolition activities in the infrastructure sector demolished quantities result in 10 Mt of rubble (plus other waste streams). Eighty percent of the resulted rubble is recycled into "secondary aggregates", which is close to the average rate in Germany (78%) [47]. These recycling rates are higher than in many EU countries [48], and are in accordance with the European goal of reaching a 70% recycling rate [49].

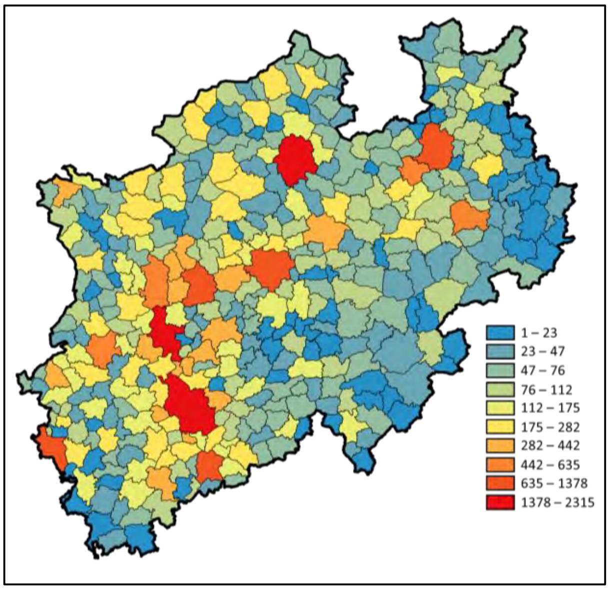

Figure 2: Residential construction (apartments) in NRW in 2019, visualized based on [39]

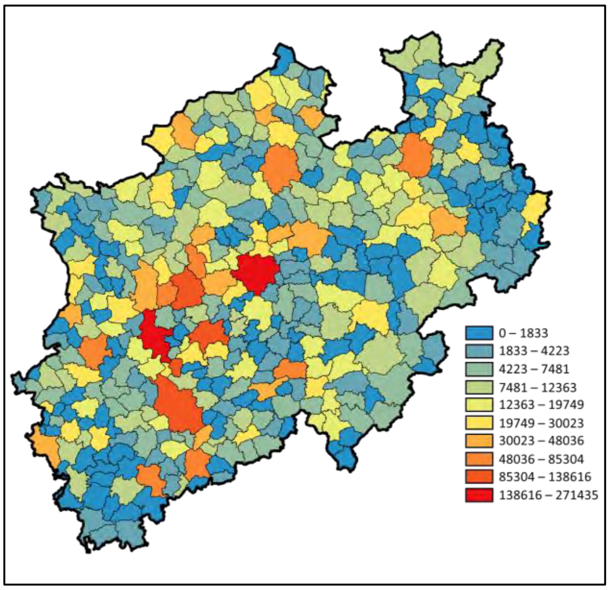

Figure 3: Non-residential construction (usable area in m^2) in NRW in 2019, visualized based on [39]

[1] Average cement content ($\frac{7\%+15\%}{2}$)

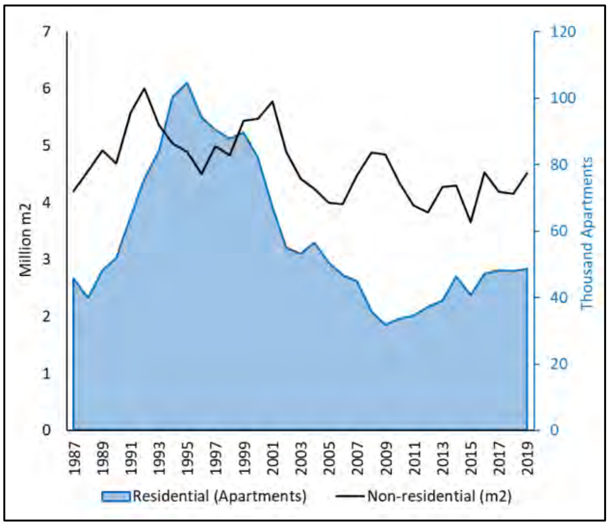

Figure 4: Construction activities in NRW, based on [39]

As Figure 5 shows, the total amounts of recycled rubble (recycled aggregates) per year has been stable during the last 15 years (Min 6.1 Mt in 2006 and max 8.5 Mt in 2018), which implies that the supply of these materials is evidently secured. Geographically, the pattern of current demolition activities match with the pattern of construction areas as shown in Figure 6.

It should be noted that 79% of the apartments in NRW were constructed after the second world war WWII [50, 39], and survival analyses show that some age classes of the apartments built after WWII have already reached or will soon enter the demolition phase (Figure 7). Therefore, CDW amounts are expected to increase in the coming decades.

In terms of composition, the rubble waste stream in Germany is composed of 51% concrete, 10% bricks and tiles while the rest is a mixture of all. Assuming an average cement content of 11% would result in a total sequestration capacity of 167 kt CO_2 in NRW. This is a quite conservative estimation as it considers only the separated concrete waste stream. Taking into account the stream mixed with bricks and tiles would result in higher capacities, but it should be preceded by a techno-economic evaluation.

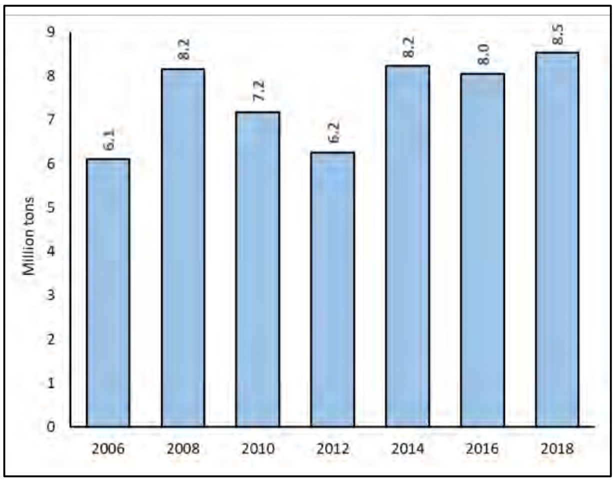

Figure 5: Amounts of rubble generated in NRW in 2019, based on [39]

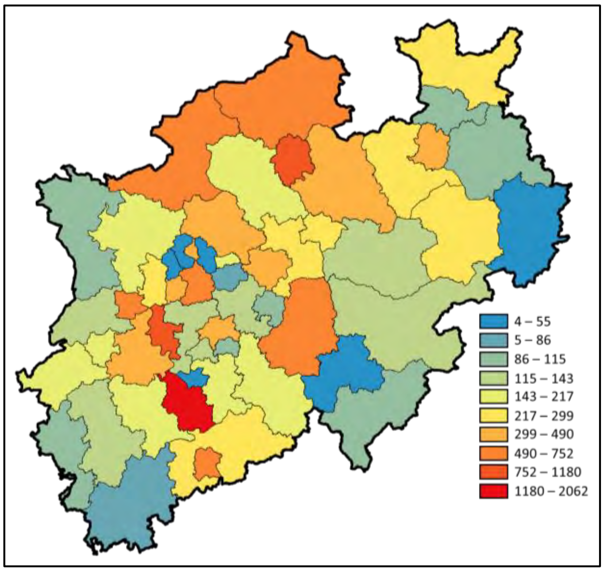

Figure 6: Locations of demolition activities (demolished rooms) in NRW in 2019, visualized based on [39]

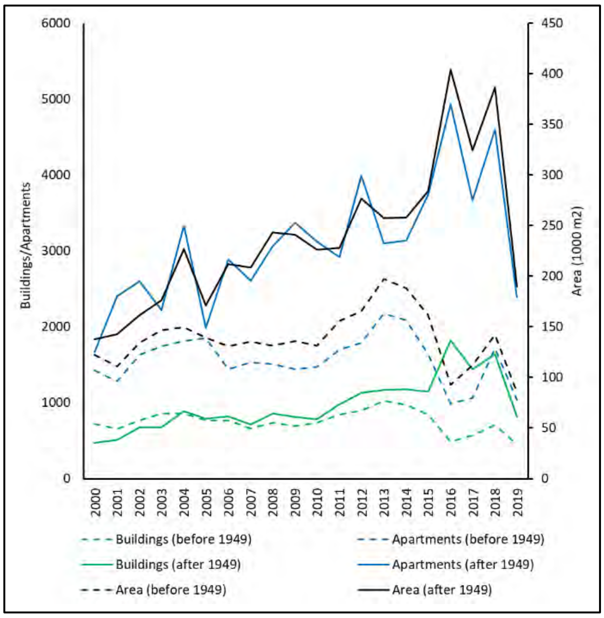

Figure 7: Demolition activities in NRW in 2019 based on [39]

Business Opportunities

In terms of the business opportunities, as mentioned, precast carbonation offers cost deductions resulting from energy savings. On the other hand, the outputs of CDW carbonation depend on the process adopted. CDW carbonation can be classified into recycled concrete aggregates (RCA) and cement waste (CW) [14].

Carbonating RCA would result in better mechanical properties than conventional recycled aggregates [51, 14] which are normally used to substitute natural aggregates. On the other hand, CW carbonation yields new physical products rather than cost savings or enhanced properties. CW can be generated during the recycling process, after pulverizing the CDW and classifying it into aggregates and WC (diameter ≤ 10 µm) [14, 41].

The main products of CW carbonation are limestone flour and residue which is composed mainly of silica dioxide. Additionally, there are CO_2 residues coming out of the carbonation chamber which can be compressed and recycled again [42, 41]. Similar to the specific carbonation capacity (ton CO_2/ton substance), the ratio of each output depends on the various factors (e.g. composition, curing process, duration, conditions, etc.).

According to [14, 23, 41, 42] , each ton of concrete waste contains 0.17 ton WC and after carbonation each ton of waste cement can sequester 0.27 ton CO_2 and produce 0.61 ton limestone flour and 0.66 residue (silica dioxide). Considering that 740 kt WC can be yielded annually in NRW, 199.8 kt CO_2 can be sequestered via carbonation in addition to 451.4 kt limestone flour and 488.4 kt residue.

Several industries consume significant amounts of limestone flour such as power, paper, glass, etc. for various purposes [52]. Figure 8 shows the limestone flour production in NRW, the yield and production value have been stable in the last ten years (average = 2.1 Mt & 28.9 EUR/ton). In addition, 16 Mt of low-value limestone are mined and consumed by cement and lime industries. Comparing the current domestic yield with the expected one from CW carbonation, it is clear that the additional amounts from carbonation will not have a negative impact on the market.

It should be noted that this figure shows only the average product value (i.e. the price at the factory gate) which does not include the value-added tax and additional profits gained by traders. The figure also represents the average value of all limestone qualities. The limestone flour produced via CW carbonation is a very high-purity limestone (> 98%) qualified to be sold at the highest price [53].

The second by-product (silica dioxide) can be used as recycled sand [42]. Figure 9 shows the annual yield and production value of construction sand in NRW, which also have been stable during the last decade (average = 17.3 Mt & 5.4 EUR/ton). Due to the low ratio between both values (488.4 kt : 17.3 Mt), the recycled sand (silica dioxide) produced via carbonation cannot cause an oversupply and thus will not have a noticeable impact on the market.

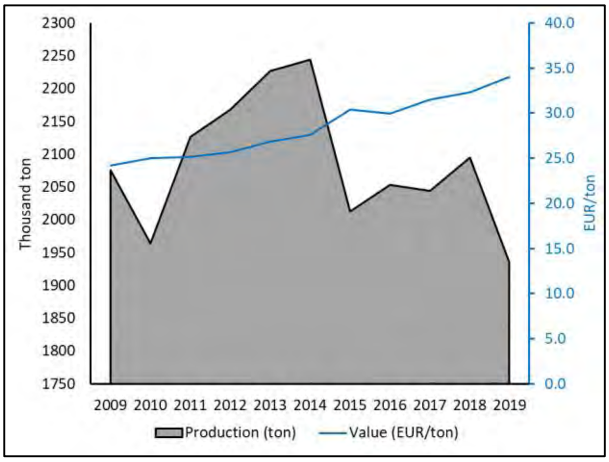

Figure 8: Limestone flour in NRW (production & value), based on [39]

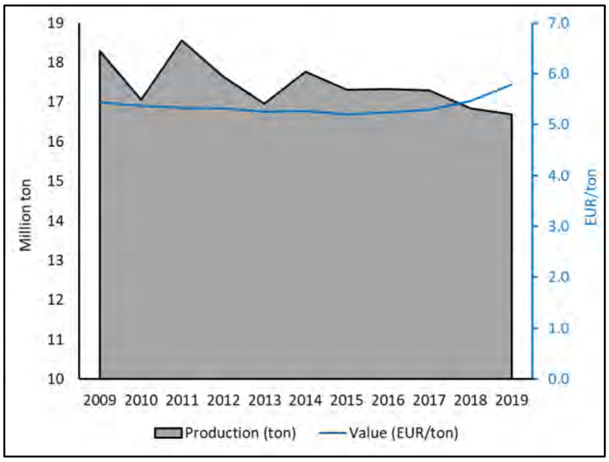

Figure 9: Construction sand in NRW (production & value), based on [39]

Nevertheless, revenues of selling these secondary products should not be considered as the sole profits resulting from carbonation. Being initially an alternative to CCS, emitters are also expected to pay a fee on each ton of carbon sequestered.

2. Case study: Using the residential and non-residential sectors as a carbon sink

A location-allocation model has been designed in order to minimize the transportation costs by means of allocating the CO_2 supply (from cement and lime plants) to the demand (carbon sinks) while considering the capacity of each sink (demand point). The model considers the concrete and precast products consumed by the residential and non-residential sectors. Due to the lack of precise data on the locations of the infrastructure activities, this sector has been omitted from the model.

To simplify the model, the cement consumed by each municipality (396 municipalities) has been aggregated on the district level (53 districts). Centers of the districts have been used to represent the locations of the carbon sinks. The supply is represented by 12 cement plants and 14 lime plants (with total process emissions of 3.2 and 2.7 Mt CO_2 respectively) as shown in Figure 8.

The residential and non-residential construction activities (Figure 2 and 3) have been used as an indicator to cement consumption in each sector. In order to illustrate the full potential, the model assumes that all concrete products are suitable for carbonation and that the maximum carbonation capacity is valid (0.35 t CO_2 per ton of cement consumed). This will result in a total sequestration capacity of 1.4 Mt CO_2. Nevertheless, it should be noted that this is an assumption regarding positive future developments and that these parameters are not yet achieved considering the state-of-the-art technology.

2.1 Methodology

As each carbon sink has a limited capacity, Capacitated P-Median problem (CPMP) has been used to allocate the lime and cement plants to the carbon sinks as algorithmically described in Equations 1 – 6 [54, 55, 56]. ArcMap 10.7.1 has been used to solve and visualize the model as shown in Figure 10.

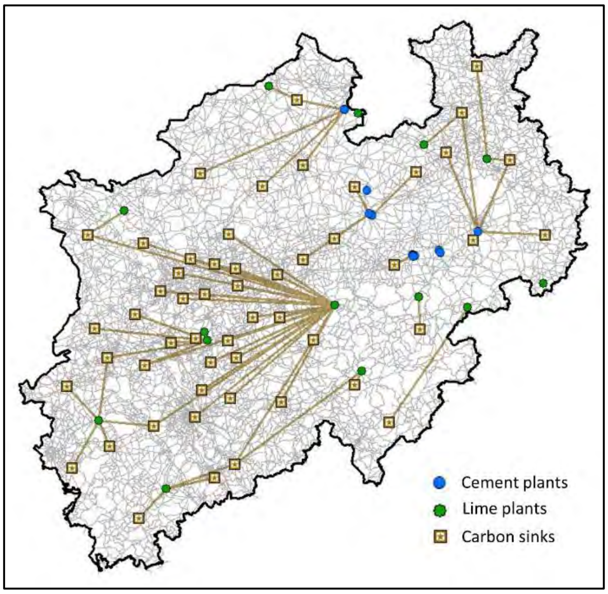

Figure 10: Location-allocation model

$$MIN\ f(x) = \sum_{i \in I} \sum_{j \in J} w_i \, . \, d_{ij} \, . \, X_{ij} \qquad (1)$$

Subject to:

$$\sum_{j \in J} X_{ij} = 1 \quad \forall i \in I \qquad (2)$$

$$\sum_{j \in J} Y_j = P \qquad (3)$$

$$\sum_{i \in I} w_i \, . \, X_{ij} \le b_j \, . \, Y_j \quad \forall j \in J \qquad (4)$$

$$Y_j \in \{0,1\} \qquad \forall j \in J \qquad (5)$$

$$X_{ij} \in \{0,1\} \qquad \forall i \in I\, , \, j \in J \qquad (6)$$

$\boldsymbol{I}$ $\;$ *set of lime and cement plants* $(i \in I = \{1, \dots, n\})$

$\boldsymbol{J}$ $\;$ *set of potential carbon sinks* $(j \in J = \{1, \dots, m\})$

$\boldsymbol{d_{ij}}$ $\;$ *the distance between plant* $i \in I$ *and sink* $j \in J$

$\boldsymbol{w_i}$ $\;$ *the amount of process emissions at* $i \in I$

$\boldsymbol{P}$ $\;$ *the number of carbon sinks*

$\boldsymbol{b_j}$ $\;$ *the capacity of a carbon sink located at* $j \in J$

$$\boldsymbol{Y_j} = \begin{cases} 1, & \text{if a carbon sink is located at site } j \in J \\ 0, & \text{otherwise} \end{cases}$$

$$\boldsymbol{X_{ij}} = \begin{cases} 1, & \text{if a plant } i \in I \text{ is assigned to a sink } j \in J \\ 0, & \text{otherwise} \end{cases}$$

2.2 Results & discussion

The model shows that the average transportation distance from the emission sources to the carbon sinks is 55.6 km. Although road transportation has the highest costs in comparison to rail and water, it is still the best transportation mode due to the low quantities of CO_2 transported and the distribution of carbon sources and sinks all over NRW. Nevertheless, the transportation costs still represent a big ratio of the carbonation costs.

In order to analyse the impact of transportation costs, a cost parameter of 0.111 EUR/ton.Km is considered representing the average of two common road transportation modes (Long Heavier Vehicles LHV) and (Tractor + trailers) with average transportation costs of 0.095 EUR/ton.Km and 0.127 EUR/ton.Km respectively [44]. Applying those figures on the average transportation distance (55.6 Km) will result in average transportation costs of 12.3 EUR/ton (round trip).

Nonetheless, the transportation costs vary significantly between the plants. Figure 11 shows the cumulative capacity utilization of carbon sinks as a function of the distance between the source and the closest available sink (presented model). Utilizing all the sequestration capacity available in the state implies that some CO_2 quantities will need to be transported 142.3 km resulting in average transportation costs of 31.6 EUR/ton, while transportation over shortest distance (8.8 Km) would cost the operators only 2 EUR/ton.

Due to the high transportation costs, the carbon price and the availability of other CO_2 sequestration options will play a major role in determining the maximum distance to be travelled between the plant and the carbon sink. This will consequently have an impact on the deployment of this technology and on the amount of CDW and concrete products that can be carbonated in the future.

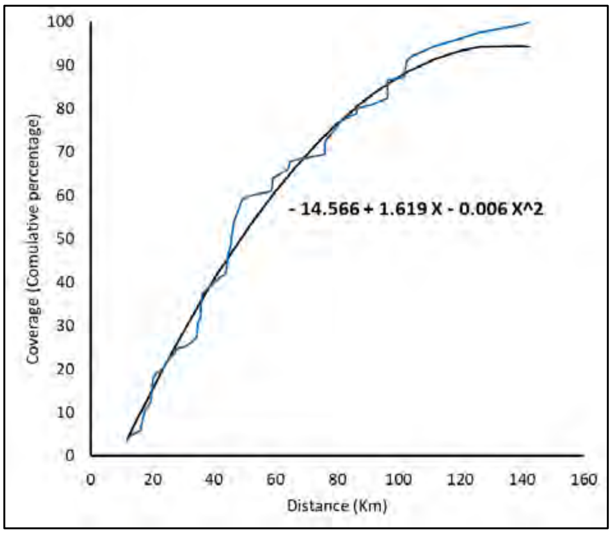

Figure 11: Distance vs. coverage of carbon sinks

In terms of the CO_2 source, the results show that more than 70% of the carbon sink capacities have been allocated to the lime plants based on the distance (transportation costs). This can be explained due to the existence of the lime plants in the western part of the state, where a lot of construction activities take place in the urban centres along the Rhine river. Thus, the lime plants have a comparative advantage in terms of the accessibility.

3. Conclusions & Outlook

Carbonation as CCU technology has potentials to be an effective substitute to CCS within certain regions, especially if there are logistics and acceptance challenges for CCS. Nevertheless, due to the limited sequestration capacity of the urban stock in NRW, carbonation will not be able satisfy the demand solely and a combination between CCU and CCS will be needed.

Investigating the development of the construction sector, the CDW recycling system and the demolition behavior in the coming decades is essential in order to quantify the capacities and reduce the investment risks associated with such novel value chains.

The locational aspects have a vital influence on the future business models of carbonation. Due to the relative small capacity of the urban carbon sinks and its distribution over the whole state (in contrast to geological storage), trucks would be the optimum transportation mode. Nonetheless, truck transportation still has the highest cost per ton and needs to be optimized.

In order to confirm the advantages of carbonation as CCU technology, RMC and recycling plants need to be investigated further from a techno-economic perspective in order to estimate the retrofitting investments. Also, it is must be analyzed how the carbonation cycle and curing chamber can be integrated within the production and recycling processes.

A full life cycle assessment LCA is required to proof the environmental benefits of the technology. Moreover, pilot projects are needed to validate the technical feasibility. Cities with high cement consumption and CWD quantities such as the urban centers (e.g. Cologne and Düsseldorf in NRW) are very suitable candidates.

Acknowledgements

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