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DemoUpCARMA

WP2 – Demonstration of CO₂ utilization and storage in concrete (domestic solution, CCUS)



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Zusammenfassung

Dieses Arbeitspaket zielt darauf ab, ein Ökosystem für die Mineralkarbonisierung zu demonstrieren, das es ermöglicht, (1) CO₂ sowohl in Primär- als auch in Recyclingbeton dauerhaft zu speichern und (2) den Energiebedarf und die Treibhausgasemissionen von Beton unter Berücksichtigung der gesamten Wertschöpfungskette zu reduzieren.

Im Folgenden werden einige finale Ergebnisse aufgeführt:

- Im Betonproduktions- und -recyclingwerk Kästli wurden zwei großtechnische, voll integrierte Technologien zur Mineralkarbonisierung in Betrieb genommen.
- Der Betrieb ergab, dass 13 kg CO₂ pro Tonne RCA im industriellen Maßstab gebunden wurden, was mit den Laborversuchen übereinstimmt und einer Steigerung von 60 % gegenüber den RECARB-Ergebnissen entspricht.
- Betonabwässer zeigten eine CO₂-Aufnahme von etwa 25 kg CO₂ pro Kubikmeter Schlamm.
- Materialtests zeigen, dass sich die Karbonatisierung positiv auf die Betonqualität auswirken kann, indem sie die Druckfestigkeit verbessert:
 - o Während der Karbonatisierung bildet sich entkalktes Calcium-Silikat-Hydrat (C-S-H) auf der Oberfläche der RCA-Partikel, was zur Zementhydratation im neuen Beton beiträgt. Dies führt zu einer verbesserten Druckfestigkeit.
 - o Die Verarbeitbarkeit von Primärbeton, welcher mit Betonabwässer produziert wird, kann durch deren vorgängige Karbonatisierung verbessert werden.
- Insgesamt wurden während des Projekts 91 t CO₂ in RCA und 4.4 t CO₂ in Betonmischwasser gespeichert. Beide Wertschöpfungsketten (CO₂-Bereitstellung und -Speicherung) verbrauchen im industriellen Betrieb weniger als 320 kWh Exergie (äquivalente Elektrische Energie) pro entnommener Tonne CO₂. Die Anlage wurde für eine jährliche Speicherkapazität von 500 t CO₂ ausgelegt (und kann auch diese Menge CO₂ speichern). Die angemessene Menge im Rahmen dieses Projekts war jedoch viel geringer, da es sich 1) um eine Erstanlage handelte. Daher war die Betriebszeit in der ersten Hälfte des Projekts gering (heute festgelegt), und 2) brach die Nachfrage nach Beton auf dem Markt in den Jahren 2022 und 2023 ein, was zu einem viel geringeren Durchsatz von Betonzuschlagstoffen in der Anlage führte als erwartet. Es wurde ein Excel-basierter Rahmen entwickelt, der die Entwicklung und den Vergleich verschiedener CCUS-Wertschöpfungsketten zur Speicherung von CO₂ in Abbruchbeton ermöglicht.



- In allen Szenarien wirken sich die CCUS-Wertschöpfungsketten positiv auf das Klima aus, d. h. sie reduzieren und entfernen mehr Emissionen als sie erzeugen. Die Szenarien, die derzeit industrielle Relevanz haben, weisen THG-Entfernungseffizienzen von über 90 % auf, d. h. die indirekten THG-Emissionen, die mit einem Lebenszyklusbewertungsansatz quantifiziert werden, betragen weniger als 10 % der aus der Atmosphäre entfernten CO₂-Menge.
- Um CO₂ dauerhaft in RCA und Gölle zu binden, muss eine Infrastruktur (CO₂ Versorgung und CO₂ Speicheranlagen) gebaut werden. Dies ist mit festen Investitionskosten verbunden, die der Hauptkostentreiber der Wertschöpfungskette sind, d. h. bei hohen CO₂ Speicherquoten sind niedrige Kosten zu erwarten. Die Kosten der CO₂-Entfernung hängen also hauptsächlich von der jährlichen CO₂ Menge ab, die im Abbruchbeton gebunden wird. Die Kosten für die CO₂ Entfernung im Rahmen des Projekts (unter Berücksichtigung aller Kosten für das Projekt) betragen 3600 CHF/t entferntes CO₂. Die Anlagen werden jedoch nach dem Projekt in den kommerziellen Betrieb übergehen und das CO₂ zu erwarteten Kosten von 261 CHF pro Tonne entfernten CO₂ entfernen - unter der Annahme einer jährlichen Entfernrungsrate von 500 t CO₂.

Résumé

Cet ensemble de travaux vise à démontrer un écosystème de carbonatation minérale qui permet (1) le stockage permanent de CO₂ dans le béton "vierge" et recyclé et (2) la réduction de la demande en énergie et des émissions de gaz à effet de serre (GES) liées à la production du béton, en tenant compte de l'ensemble de la chaîne de valeur.

Les principaux résultats du projet sont énumérés ci-après :

- Deux technologies de carbonatation minérale à l'échelle industrielle et entièrement intégrées ont été mises en service dans l'usine de production et de recyclage de béton de Kästli.
- Le fonctionnement de la technologie de carbonatation des agrégats recyclés de béton (ARB) montre que 13 kg de CO₂ par tonne de ARB ont été séquestrés à l'échelle industrielle. Cela confirme les expériences à l'échelle du laboratoire et correspond à une augmentation de 60 % de la capacité de stockage par rapport aux résultats du projet RECARB.
- La boue de recyclage (eau de lavage obtenue lors du nettoyage des camions transportant le béton) a montré une absorption de CO₂ allant jusqu'à 25 kg par mètre cube de boue.
- Les tests de matériaux montrent que la carbonatation peut avoir un effet positif sur la qualité du béton en améliorant sa résistance à la compression :



- Du C-S-H décalcifié se forme à la surface des particules contenues dans l'ARB pendant la carbonatation, contribuant à l'hydratation du ciment dans le nouveau béton. Il en résulte une amélioration de la résistance à la compression.
 - L'ouvrabilité du béton "vierge" utilisant des boues peut être améliorée en le carbonatant au préalable.
- Au total, 91 t de CO₂ ont été stockées dans l'ARB et 4.4 t de CO₂ dans la boue de recyclage tout au long du projet. Les deux chaînes de valeur (approvisionnement en CO₂ et stockage) consomment moins de 320 kWh d'exergie (travail électrique équivalent) par tonne de CO₂ stockée dans le cadre de l'exploitation industrielle. L'usine a été conçue pour une capacité de stockage annuelle de 500 t de CO₂ (et peut également stocker cette quantité de CO₂). Cependant, la quantité adéquate dans le cadre de ce projet était bien inférieure car 1) il s'agissait d'une première installation de ce type. Ainsi, le temps de fonctionnement dans la première moitié du projet était faible (résolu aujourd'hui), et 2) la demande de béton sur le marché en 2022 et 2023 s'est effondrée, ce qui a entraîné un débit de granulats de béton dans la centrale moins important qu'attendu.
- Un outil d'analyse de cycle de vie (ACV) basé sur Excel a été développé. Il permet de développer et de comparer différentes chaînes de valeur CCUS stockant le CO₂ dans le béton de démolition par rapport à différents indicateurs environnementaux.
- Dans tous les scénarios, les chaînes de valeur CCUS ont un impact positif sur le climat, c'est-à-dire qu'elles réduisent et stockent plus de CO₂ qu'elles ne génèrent d'émissions de GES. Les scénarios qui présentent actuellement un intérêt industriel affichent des rendements d'élimination des GES supérieurs à 90 %. Cela signifie que les émissions indirectes de GES (quantifiées à l'aide de l'outil ACV) représentent moins de 10% de la quantité de CO₂ éliminée de l'atmosphère.
- Pour fixer le CO₂ de manière permanente dans l'ACR et le lisier, il faut construire une infrastructure (approvisionnement en CO₂ et usines de stockage de CO₂). Cette infrastructure a un coût d'investissement fixe - qui est le principal facteur de coût de la chaîne de valeur, c'est-à-dire que lorsque les taux de stockage du CO₂ sont élevés, on s'attend à des coûts faibles. Ainsi, le coût de l'élimination du CO₂ est principalement fonction de la quantité annuelle de CO₂ séquestrée dans le béton de démolition. Le coût de l'élimination du CO₂ dans le cadre du projet (en tenant compte de tous les coûts du projet) était de 3600 CHF/t de CO₂ éliminé. Cependant, les usines entreront en exploitation commerciale après le projet, éliminant le CO₂ à un coût prévu de 261 CHF par tonne de CO₂ éliminée - en supposant un taux d'élimination annuel de 500 t de CO₂.



Summary

This work package aims to demonstrate a mineral carbonation ecosystem that allows (1) storing CO₂ permanently in both primary and recycling concrete and (2) reducing the energy demand and greenhouse gas (GHG) emissions of concrete considering the entire value chain.

The key results of the project are the following:

- Two industrial-scale, fully integrated mineral carbonation technologies have been commissioned at the Kästli concrete production and recycling plant.
- The concrete aggregate carbonation technology operation shows that 13 kg of CO₂ per ton of RCA have been sequestered at an industrial scale, confirming laboratory-scale experiments and corresponding to an increase of 60% in storage capacity compared to the RECARB project results.
- Recycling slurry (washing water obtained from cleaning the concrete trucks) showed a CO₂ uptake of up to 25 kg CO₂ per cubic meter of slurry.
- Material tests show that carbonation can have a positive effect on concrete quality by improving its compressive strength:
 - o Decalcified calcium-silicate-hydrate (C-S-H) is formed on the surface of RCA particles during carbonation, contributing to cement hydration in new concrete. This results in an improved compressive strength.
 - o The workability of primary concrete using slurries can be improved by carbonating it prior.
- Overall, 91 t CO₂ has been stored in RCA and 4.4 t CO₂ in concrete mixing water throughout the project. Both value chains (CO₂ supply & storage) consume less than 320 kWh of exergy (electrical equivalent work) per t of CO₂ removed in industrial operation. The plant was designed for an annual storage capacity of 500 t CO₂. However – the adequate amount within this project was much lower because 1) it was a first-of-its-kind plant. Thus, the up-time in the first half of the project was low (fixed today), and 2) the demand for concrete on the market in 2022 and 2023 collapsed – resulting in a much lower throughput of concrete aggregate through the plant than anticipated.
- An Excel-based life-cycle assessment (LCA) framework has been developed, which allows the development and comparison of various CCUS value chains storing CO₂ in demolition concrete.
- In all scenarios, the CCUS value chains positively impact the climate, i.e., they reduce and remove more emissions than they generate. The scenarios that currently have industrial relevance show GHG removal efficiencies exceeding 90%, i.e., indirect GHG emissions (quantified with the LCA tool) amount to less than 10% of the CO₂ removed from the atmosphere.



- To fix CO₂ permanently in RCA and slurry, infrastructure (CO₂ supply and CO₂ Storage plants) has to be built. It comes at a fixed investment cost – which is the main cost driver of the value chain, i.e., at high CO₂ storage rates – low costs are expected. Thus, the cost of CO₂ removal is mainly a function of the annual amount of CO₂ sequestered in demolition concrete. The cost of removing CO₂ within the project (accounting all costs to the project) was 3600 CHF/t CO₂ removed. However – the plants will enter in commercial operation after the project, removing the CO₂ at an expected cost of 261 CHF per ton of CO₂ removed – assuming an annual removal rate of 500 t of CO₂.



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1 Introduction

1.1 Background information and current situation

Switzerland aims to reduce its impact on the global climate system within the national borders to net-zero by 2050. Switzerland's Long-Term Climate Strategy² outlines that of the 51.5 Mt CO₂-eq emissions in 2020, 77% can be reduced while 23% or 11.8 Mt CO₂-eq emission need to be addressed with Carbon Capture, Transport, and Storage (CCTS) or Negative Emission Technologies (NET).

While CCTS and NET form a key pillar of the Swiss climate strategy, the sector is still in a nascent phase globally, and the Swiss industry has little experience with such technologies. Moreover, the scale at which NETs, such as direct air carbon capture and storage (DACCS) and bioenergy carbon capture and storage (BECCS), operate today is in the single-digit kiloton range – thus, they have 30 years left to grow by six orders of magnitude to contribute the required impact.

One key element of CCTS and NET is that after a CO₂ molecule has been captured, it needs to be permanently stored so it cannot re-enter the atmosphere with negative effects on the climate. The two ways to fix CO₂ permanently are CO₂ storage in suitable geological formations and in-situ and ex-situ CO₂ mineralization. Both approaches have their limitations. Geological storage requires dedicated geological formations, and Switzerland's geology has not been sufficiently explored to make robust statements on CO₂ storage potential to be exploited in the future. CO₂ mineralization on the other hand requires access to large amounts of reactive mineral materials as feedstock. In the scope of the DemoUpCARMA project, WP2 focuses on ex-situ CO₂ mineralization using industrial waste materials, whereas WP3 on in-situ mineralization, exploiting underground basalt rocks.

Demolition concrete, the most significant solid waste stream humans handle, can store CO₂. Concrete carbonation has been known for decades: In principle, CO₂ undergoes a chemical reaction with the cement hydrates and partially transforms them to CaCO₃. More details can be found elsewhere³.

Prominent companies and research initiatives developing carbon negative construction materials from industrial wastes (e.g. slags, demolished concrete) are Carbon8 (UK), Carbstone (BE), Sika (CH), FastCarb (FR) and Blue Planet (US). Neustark's most direct competitors are Blue Planet, FastCarb and Sika, who also work with demolished concrete as a raw material. The CO₂ storage technologies developed by CarbonCure (CA) and Solidia (US) are to be viewed as complements to Neustark's solution. Within the concrete mix, CarbonCure and Solidia add CO₂ to the fresh cement whereas Neustark adds CO₂ to the recycled concrete aggregate and to the recycled mixing water. A systematic overview of the different initiatives is given in the table below.

² Switzerland's Long-Term Climate Strategy, 2021.

³ Tiefenthaler J, Braune L, Bauer C, Sacchi R and Mazzotti M (2021) Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector. *Front. Clim.* 3:729259



COMPANY	RAW MATERIAL	PRODUCT	STAGE	DESCRIPTION/ FEATURES	LIMITATIONS
Sika	Demolished concrete	- Regenerated primary materials -Mortar poder	Pilot	Aggregate is broken down into its original components gravel and mortar by a combined attrition and direct carbonation process.	No utilisation path for fine mortar powder. Transportation of aggregates (centralised production vs. de-centralised application).
FastCarb	Demolished concrete	Carbonated concrete aggregate	Pilot	Direct carbonation of demolished concrete either in continous mode at the cement plant or batch mode at the recycling site.	In case of deployment at cement pant: Transportation of aggregates (centralised production vs. de-centralised application). In case of deployment at recycling plant: container based batch process causes significant operational cost
Blue Planet	Demolished concrete	Synthetic Aggregate	Pilot	Calcium is first leached from demolished concrete aggregates. In a second step a synthetic limestone aggregate is produced by carbonating the leached calcium.	Transportation of aggregates (centralised production vs. de-centralised application). Compatibility of new synthetic aggregate with existing regulation, norms and proceses.
Carbon8	Slags	Synthetic Aggregate	Pilot	Production of synthetic aggregate through carbonation of slags.	
Carbstone	Slags	Pre-fabricated	Pilot	Production of pre-fabricated elements	Application limited to pre-fabricated elements.



		concrete elements		through carbonation of slags.	
CarbonCure	Fresh concrete	Carbonated fresh concrete	Commercial	Carbonation of cement during concrete batching.	Only a few hundred Grams of CO ₂ are sequestered by m ³ of concrete.
Solidia Technologies	Fresh concrete	Pre-fabricated concrete elements	Pilot	Curing of concrete with CO ₂ instead of water.	Application limited to pre-fabricated elements.
Neustark	Demolished concrete Concrete mixing water	-Carbonated concrete aggregate -Carbonated fresh concrete -Carbon Dioxide Removal Certificates	Pilot	Direct carbonation of demolished concrete at the concrete recycling site. Full solution including CO ₂ sourcing and delivery from biogenic sources, patent-pending measurement system for CO ₂ uptake and monitoring and marketing of carbon dioxide removal certificates.	

In summary, the Neustark system is the only one coming with the following combination of attributes:

1. Seamless integration into processes at the concrete recycling site. This is key as any extra transportation of recycled construction aggregate will render continuous economic carbonation impossible.
2. 100% of the products of the process can be reused and are 100% compatible with existing norms, regulations and industry practices.
3. Full solution including CO₂ supply and incentive system for concrete recyclers through redistribution of carbon dioxide removal revenues.



The Swiss construction sector recycles this material stream in large quantities at concrete recycling plants, often co-located with a concrete batching plant. In the scope of the RECARB⁴ project, an industrial consortium constructed and operated a first-of-a-kind industrial-scale container-based system for carbonating demolished concrete aggregate. Operation at six recyclers across Switzerland showed that the technology works at an industrial scale and that the carbonated concrete aggregate can be used as an aggregate for ready-mix concrete. In the operation at Kästli Bau, CO₂ uptakes of approximately 8 kg CO₂ per ton of aggregate have been achieved. Moreover, a life cycle assessment determined the environmental impact, showing that the storage of 1000 kg of CO₂ emits 50 kilograms of CO₂ equivalent due to the use of energy and materials along the value chain. Furthermore, the RECARB project revealed that carbonation may help to reduce the cement content and, thus, the embodied emissions of ready-mix concrete by 5-10% depending on the concrete aggregate.

Energy and CO₂ potential

Previous work in the scope of RECARB enables to develop a number of working hypothesis – which need to be validated in the scope of this project. It is assumed that 10 kg of CO₂ can be stored in 1 ton of RCA or in 1 m³ of cement water respectively. Furthermore, it is assumed that 1000 kg of carbonated RCA and 170 liter of cement water are used per m³ of concrete. Therefore, 11.7 kg of CO₂ are stored per m³ of concrete.

Besides serving as a CO₂ sink, preliminary material tests show, that carbonated RCA features improved compressive strength compared to non-carbonated RCA – while the physical principles behind that are not well understood yet. The improved characteristics of carbonated RCA and the carbonated cement water can lead to a reduction of the cement content in concrete compared to conventional recycling concrete, while still complying with the required standards.

For the extrapolation it is assumed that the cement content can be reduced by 15 kg/m³ concrete in the case of carbonated RCA as compared to non-carbonated RCA. In turn, cement of type CEM II/B has a carbon footprint of 0.62 kg CO₂-eq/kg cement⁵.

The technology aims at direct and indirect energy savings. By reducing the cement content, less cement needs to be produced resulting in direct energy savings. In addition, in a climate neutral world, we are no longer allowed to emit CO₂. Thus, all positive emissions have to be compensated by negative emissions.

To take CO₂ out of the atmosphere requires most probably the deployment of Direct Air Capture at large scale. Therefore, DAC would be the alternative. DAC first generates a purified CO₂ stream from air (0.04% CO₂). This comes at a significantly higher energy penalty as shown in the table.

⁴ Recarb – CO₂ negative Betonrecycling mittels Karbonatisierung
(<https://www.aramis.admin.ch/Texte/?ProjectID=47360>)

⁵ Ecoinvent version 3.6, 1 kg cement, alternative constituents 21-35% {CH}|market for allocation, cut-off by classification.



Energy Balance (electricity and heat).

	DAC (Deutz and Bardow, 2021)		CO ₂ Mineralization (RCA and cement water)	
	Per ton CO ₂ stored		Per ton CO ₂ stored	Per m ³ concrete
Electricity capture [kWh/tCO ₂]	700		0	0
Electricity Liqu. [kWh/t CO ₂]	-		280	3.3
Heat supply [kWh/t CO ₂]	4611		0	0
Energy for CO ₂ transport [kWh/t CO ₂]	-		7	0.1
Electricity for CO ₂ storage [kWh/t CO ₂]	101		51	0.6
Avoided energy through cement reduction (mostly heat)	-		-1095	-11
Total	5412		-757	-7

According to Deutz and Bardow (2021)⁶, an adsorption-based DAC plant in Switzerland emits around 180 kg CO₂-eq. per ton CO₂ stored. With a Suisse electricity mix, the mineralization of CO₂ in RCA emits around 69 kg CO₂-eq. per ton CO₂ stored and the carbonation of cement water leads to the emission of 85 kg CO₂-eq. per ton CO₂ stored.

⁶ Deutz, Sarah, and André Bardow. "Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption." *Nature Energy* 6.2 (2021): 203-213.



CO₂ balance.

	DAC and geological storage		CO ₂ Mineralization (RCA and cement water)	
	Per ton CO ₂ stored		Per ton CO ₂ stored	Per m ³ concrete
kg negative emissions per ton of CO ₂ stored	820		929	10.9
Kg of avoided emissions per ton of CO ₂ stored	-		930	9.3
Total	820		1859	20.2

Business model and market potential

Neustark sells its carbonation plants to concrete recyclers and producers, provides them with the necessary CO₂ and permanently monitors the CO₂ uptake across all installations. CO₂ certificates are then issued according to a third party verified methodology and marketed to customers on the voluntary and compliance carbon markets. Those certificate revenues are to a large extent redistributed to the concrete recyclers and producers so that they have an incentive to store as much CO₂ as possible. The carbonated concrete aggregates and carbonated concrete continues to be sold by the concrete recyclers and producers. Builders are the end customers for those products. They only need to pay an extra price if they want to credit the CO₂ stored in the buildings on their construction projects as in this case no certificates can be sold.

We expect that the necessary certificate price will be in the range of CHF 250 – 350 per ton to cover the cost for all the following necessary positions: capture of biogenic CO₂, liquefaction, transportation, permanent storage, monitoring, capital cost. The indicated price range applies to Neustark solutions that are deployed as of today in Switzerland and which are supplied with CO₂ from our very first small-scale CO₂ liquefaction at the Bern Wastewater Treatment Plant (250kg CO₂/h capacity).

Around 80% of the total cost relate to capture, liquefaction and transportation of CO₂. This cost is not specific to Neustark but inevitable to any CO₂ which is captured at any point source. We are very confident that the Neustark solution will always be the cheapest storage solution for concentrated CO₂ captured at Swiss point sources as international transportation of CO₂ can be avoided.



Lower price levels might be possible with bio-based solutions such as afforestation, biochar or soil carbon. Those approaches however don't allow to store pure streams of captured CO₂ and come with a lower storage permanence. To our knowledge demolished concrete and other mineral wastes are the only permanent CO₂ storage solution available in Switzerland as of today.

Beyond that, the project also revealed implementation barriers for this value chain – which can also be viewed as opportunities:

1. **Usability & Costs:** The costs of storing CO₂ have to be lower than the price paid for reducing the emission of that CO₂. Additional material handling makes the technology economically non-viable at current (and probably future) rates. For this reason, the technology needs to be integrated so that material handling efforts are kept at the same original level or even reduced if possible. Moreover, one key lever for optimizing the use of capital is to maximize the amount of CO₂ stored per site – looking at further opportunities to fix CO₂.
2. **Optimal material use:** Though it has been shown that carbonation of concrete aggregate at worst does not impact the mix design in undesired ways, the physical and chemical mechanisms behind the observed improvements have not been understood well. However, understanding how one can use carbonation to improve the mix design can cut the embodied emissions of concrete and, at the same time, support the economics of such a solution – which will result in more widespread use and even more impact.
3. **Climate Impact Assessment:** Carbon dioxide removal technologies must work in a net-zero environment, in addition to genuinely removing CO₂ from the atmosphere permanently. Such technologies must be embedded in the existing industrial landscape to assess this. Such a procedure exhibits a significant complexity level, requiring experts to determine the effective climate impact.

1.2 Purpose of the WP

This WP aimed to advance the maturity of the value chain so that the Swiss (and global) concrete recycling industry could adapt it quickly as their production standard. Thus, the three major challenges listed above were addressed as follows:

Usability/costs

The level of system integration mainly drove the usability of the plant. Ideally, the concrete recycler did not have to realize that the concrete aggregate was carbonated on a daily basis. Moreover, in the



predecessor project RECARB⁷, which was demonstrating a mobile, container based, industrial scale CO₂ mineralization system for concrete aggregate, the costs were predominantly affected by the additional material handling efforts and by the plant's throughput of CO₂.

To increase the usability and reduce the associated cost of the mineralization system, two existing silos of the Kästli Bau concrete plant were retrofitted with a CO₂ storage system. Since the aggregate passed anyway through the silos then, the material handling efforts were kept at the same level (and additional handling like in RECARB could be mitigated).

Moreover, besides concrete aggregate, most concrete plants produce a slurry rich in cement, resulting from the routine washing of concrete batching systems and of concrete delivery trucks. The system was equipped with a slurry carbonation plant – thus increasing the CO₂ storage capacity of a single plant – that shares the CO₂ supply infrastructure with the aggregate silos.

The systems were operated for 15 months to gain operational experience and to reduce uncertainty and risk. The main parties involved were Neustark and Kästli.

Optimal material use

Concrete recyclers and concrete plants needed to be assured that they could utilize the carbonated material for their products (e.g., concrete). Beyond that, it was good for the environment and for the economics to minimize the clinker content of concrete mix designs.

The lead of this task was at Empa, who first studied the effect of carbonation on the properties of concrete aggregate and concrete slurry, and then investigated the impact of carbonation on concrete workability and on its mechanical properties. In the second half of the project, they explored the potential to reduce the cement content of concrete mix designs and investigated the durability properties of such mix designs. They collaborated closely with Kästli Bau to align the EMPA research activities with the Kästli industrial practices.

Climate Impact Assessment

A Life Cycle Assessment (LCA) framework for accounting for greenhouse gas emissions and other environmental impact metrics as defined by the Environmental Footprint v.3.0 had to be developed and fed with data. The quality of the assessment depended highly on the quality of the data provided. PSI developed a framework according to which the LCA was conducted. In collaboration with Neustark, a data collection procedure was implemented, and the data from the value chain operation was monitored and shared. In this way, PSI could feed its modeling framework with industry data and investigate various scenarios to improve the understanding of the environmental key impact factors of the value chains.

⁷ Recarb — CO₂ negatives Betonrecycling mittels Karbonatisierung - Texts (admin.ch)



1.3 Objectives

- Demonstrate the technical feasibility of a mineral carbonation value chain using and permanently storing CO₂ in (1) recycled concrete aggregate (RCA) and (2) in concrete mixing water.
- Demonstrate the integration in the concrete manufacturing plant of a brand-new carbonation technique based on using siloes instead of containers, thus enabling easier operation and a greater extent of carbonation.
- Develop an understanding of the carbonation of RCA and concrete mixing water to allow the optimization of concrete mix designs in terms of energy efficiency and environmental performance by performing rigorous Life Cycle Assessment (LCA).
- Operate and validate the overall value chain at TRL 7/TRL 8 in collaboration with concrete manufacturing plants, using and storing 500 t of CO₂ over 15 months.

Moreover, as per the aims of the project, we quantify the following KPIs:

- Exergy consumption⁸, with a target of 150 to 300 kWh/t CO₂ removed
- Net CO₂ removal efficiency, with a minimum target of 85%
- Cost of CO₂ removed, with a target of 250 to 350 CHF/t CO₂ removed

⁸ Exergy represents the amount of energy converted into the equivalent electricity. Thus, e.g. fossil fuels are converted into Exergy by using the efficiency factor of e.g. a thermal power plant converting it into electricity, e.g. 40%. <https://doi.org/10.3929/ethz-b-000530962>



2 Description of facility

Design, construction & commissioning of mineral carbonation plants (Task 1)

The steps to get an operating plant follow a typical plant construction process – in a simplified form described in the following.

First, a project plan was set up in the project planning phase, a project manager was assigned, and a kick-off meeting with Kästli Bau took place. Second, in the initial engineering phase, the plant layout, the P&ID, and a functional description were developed according to the customer's requirements. Third, the bill of materials, a foundation plan, detailed sealings and CO₂ injection systems drawings, and risk analysis were delivered in the detailed engineering phase. Fourth, a clear plan for the assembly and plant commissioning was developed in the construction planning phase. Fifth, in the construction phase, the plant was assembled on-site. Finally, the commissioning of the plant took place by testing the electrical signals, the control routine, conducting pressure tests followed by a system test, and the start-up of the plants.

The aggregate carbonation plant (visualization in Figure 1 and Figure 2) and the slurry carbonation plant (Figure 3) passed through the same type of workflow.



Figure 1. The figure shows the layout of the aggregate carbonation plant from the bird's perspective. The liquid CO₂ storage tank is located at the top left corner. From there, a pipe guides the CO₂ to the reboiler, placed to the right of the CO₂ storage tank. Below the CO₂ reboiler, the process control cabinet is placed. From there, the CO₂ is guided to two silos. Silo 1 has a rectangular shape and can be seen in the bottom left corner; the other has a circular shape and can be seen in the bottom right corner.

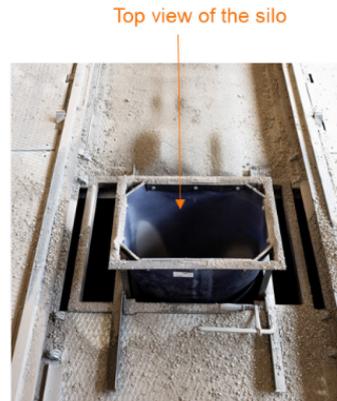
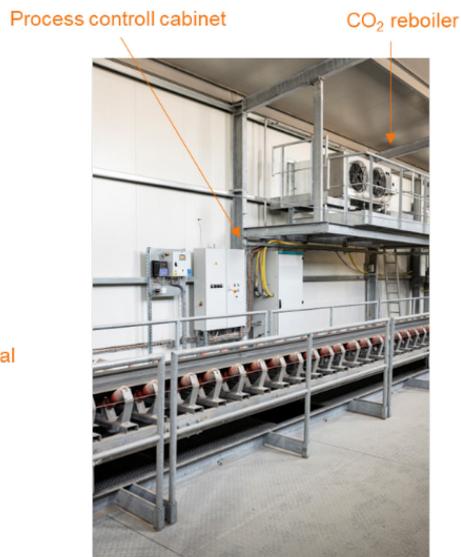
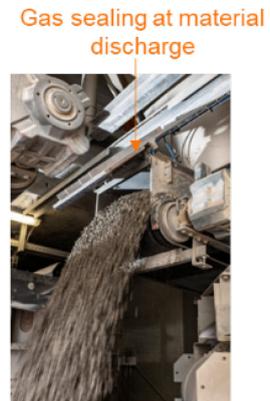


Figure 2. The images show the key components of the aggregate carbonation plant.



Figure 3. The slurry carbonation system is shown (front left side). The slurry is contacted with CO₂ shortly after the inlet of the pipe. Afterward, it is pumped through the piping system equipped with static mixers to maximize the CO₂ mass transfer from the gas to the liquid phase. The vessel at the left separates the slurry from the not-absorbed gas phase. Afterward, the slurry is returned to the collection basin. In the background, a container is placed, which is used for the start-up phase of the technology. Afterward, the plant was placed on top of the slurry collection basin.

Operational concept of the plants (Task 3)

The operation of the plant was split into two phases: A ramp-up phase, lasting until 31.12.2022, and a production phase starting on 1.1.2023. The ramp-up phase identifies and resolves problems typically encountered in first-of-a-kind plants. Moreover, the aim was to identify an operating point for the plant and to reach stable, uninterrupted operation so that the plant could switch to production mode in 2023. In the production mode, the main aim is to maintain a regular process and monitor LCA data.

Operational concept: CO₂ Supply

The carbonation plant embodies a liquid CO₂ storage tank that can hold up to 30 t of CO₂. Invariably, when the tank level drops below 10 t of liquid CO₂, a truckload of about 20 t of CO₂ is delivered from the CO₂ liquefaction operated by Neustark on-site at the wastewater treatment plant Ara Bern.



Operational concept: Concrete aggregate carbonation

Typically, the silos are filled or topped up with concrete aggregate just before the operation of the plant stops at night. The operator switches on the carbonation system from his control room. A flow of CO₂ is injected into the silos. Over time, the flow is reduced such that the CO₂ mineralization and the CO₂ injection rates are equivalent, and the CO₂ remains within the silo. After a certain period, e.g., 12 hours, the process is stopped, and the material is used over the day. The next day, the same procedure starts again.

Operational concept: Slurry carbonation

The plant was placed on top of the slurry collection basin. The slurry is pumped through a static mixer – where it is in contact with CO₂. The CO₂-enriched slurry is returned to the basin. We can monitor the amount of CO₂ sequestered, the pH value, and the CO₂ concentration in the basin's overhead to control and stop the process.

Concrete mix designs (Task 2)

Natural aggregates (NA, alluvial sand, and gravel) and RCA delivered by Kästli AG were stored in big bags and silos (Figure 4). Typically, 50-75 liters of concrete batches were produced in the Empa facilities (Figure 5). On the one hand, concrete with only NA was produced in combination with recycling slurries. On the other hand, the recycling concrete contained 60 mass-% of RCA, and 40 mass-% NA produced both with and without slurry. The reference cement used in modules 1 and 2 was a Portland limestone cement (CEM II/A-LL 42.5 N) containing about 80 mass-% cement clinker.

Provided that about 95 % of the concrete produced in Switzerland are the types A, B, and C according to SN EN 206-1:2013, types A and C were selected. The requirements for the concrete mix design for type A are a minimum cement content of 280 kg/m³ and a maximum water-to-cement ratio of 0.65. For type C, the corresponding values are a minimum cement content of 300 kg/m³ and a maximum water-to-cement ratio of 0.50. Using these prescribed boundary conditions, the content of aggregates is usually around 1750 (recycling concrete) and 1900 (primary concrete) kg/m³.



Figure 4. Storage of the RCA in big bags (1) and silos (2) and the slurry in barrels (3) at Empa.

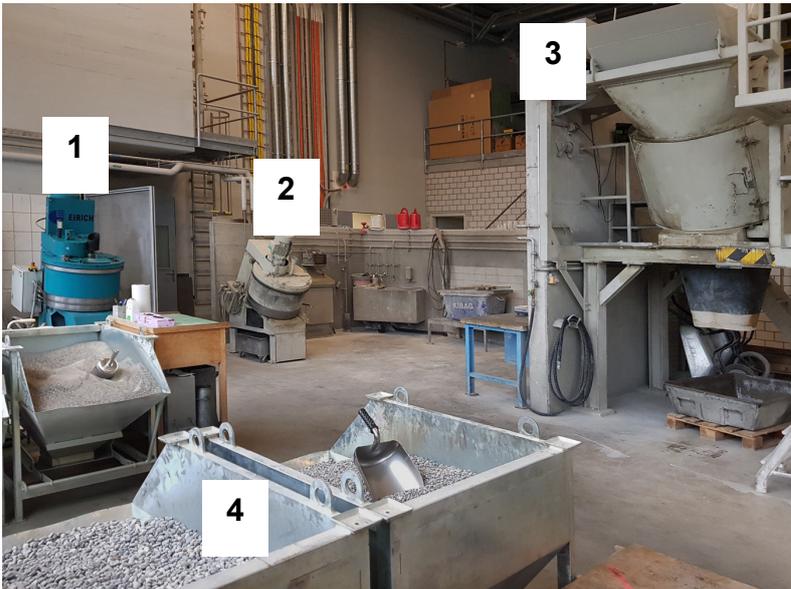


Figure 5. The concrete laboratory at Empa has two 75-liter mixers (1, 2) and a 250-liter mixer with ready-to-use concrete aggregates in containers (4).



3 Procedures and methodology

Physical principles of carbonation of concrete aggregate and slurry (Task 1)

Mineralization of CO₂ in concrete is a reaction in concrete structures exposed to a CO₂ source, e.g., ambient air or pure CO₂. More precisely, the carbonation reaction takes place in the pore water. The hydrated cement phases (mainly portlandite (Ca(OH)₂) and calcium silicate hydrates = C-S-H) form a solid-liquid equilibrium with the pore solution, which is saturated with respect to these minerals and exhibits a pH value typically exceeding 12. Simultaneously, CO₂ is absorbed by the pore solution, speciates to carbonate and bicarbonate ions, and diffuses along the pores towards the center of the aggregate. As more CO₂ is absorbed, the pore solution gets supersaturated with respect to CaCO₃, which precipitates. As more CaCO₃ precipitates, the pore solution is again undersaturated with respect to the cement hydrates – which keep dissolving and transforming into calcium carbonate until they are partially to entirely carbonated. Factors impacting the propagation and extent of carbonation are the CO₂ partial pressure, the temperature, the pore structure and effective surface area of the material, and the water saturation of the pores. We want to refer to another study published in this context⁹ for further information.

In the previous paragraph, the carbonation phenomenon of concrete aggregate was described. However, they remain the same for slurry carbonation, where the bulk liquid replaces the pore solution. Since the particle diameter of slurry particles is typically in the micrometer range, the carbonation time can be shortened from hours to minutes.

Data monitoring concept of the industrial demonstration (Task 3)

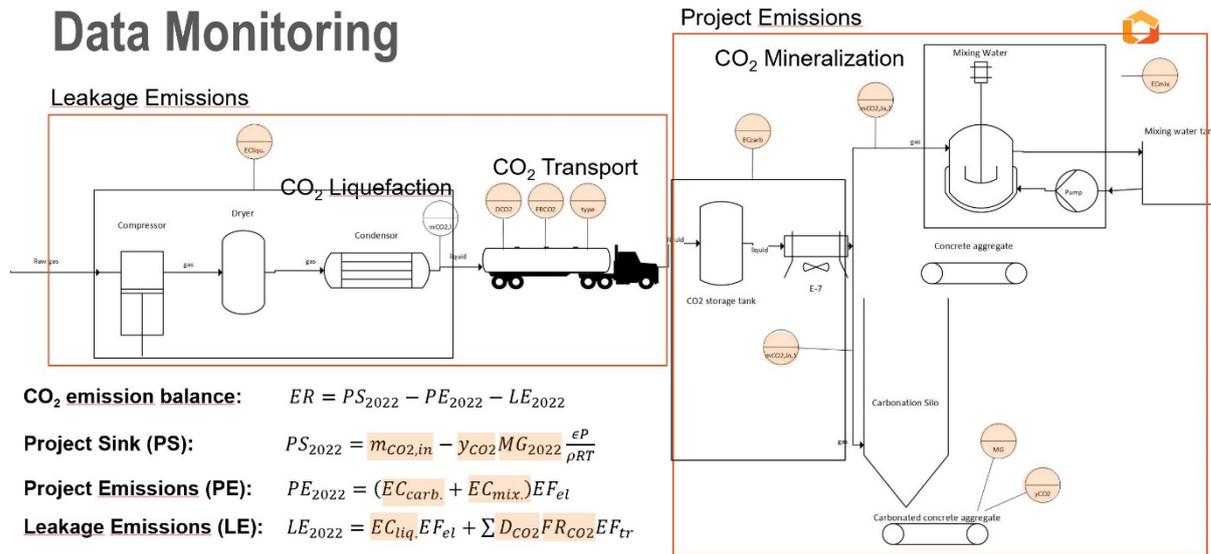
The overall value chain operating in the DemoUpCARMA project consists of the CO₂ liquefaction located at Ara Region Bern, transport of CO₂, and its mineralization at the Kästli Bau recycling plant.

Two mineralization options are investigated in WP2. Technology 1 mineralizes CO₂ in concrete aggregate, temporarily stored in the carbonation silo. Technology 2 mineralizes CO₂ in the concrete, mixing water/ slurry. The following data monitoring concept will describe 1) the data sets collected along

⁹ <https://doi.org/10.3389/fclim.2021.729259>



the value chains and 2) we will rationalize how the resulting KPIs are calculated based on these data sets.



The monitoring data including LCA datasets form the Life Cycle Inventory (LCI) for this project. PSI & ETH will use it for their evaluation.

5

Figure 6. A flow chart of the overall system is shown. It contains the CO₂ liquefaction (at the left), the CO₂ transport, and the CO₂ mineralization. Moreover, according to the Gold Standard methodology, the equations listed are used to determine the emission reductions resulting from this project¹⁰.

Figure 6 visualizes the mineral carbonation value chain conceptually. The system boundaries for the monitoring data are drawn around the processes operated and controlled by Neustark – thus generating data sets we can access. However, the rationale behind these system boundaries is that they include all additional steps necessary to store CO₂ permanently as carbonate minerals. To obtain a complete picture, one must assess if these value chains and their products generate upstream and downstream impacts that differ from the baseline. PSI conducts this task. Empa and Kästli Bau did provide input data for these potential up- and downstream impacts. The data monitored serves as an input to the environmental and economic evaluation of the system. The drawn system boundaries outline which type of data sets are collected within the 15-month demonstration of the chain.

The data sources are, on the one hand, sensors (such as flow meters, scales, electricity meters, pH-electrodes, T and p-sensors), specification sheets of equipment (e.g., type of truck, type of material), and calibrated values (e.g., density and particle size of material).

¹⁰ Gold Standard Methodology: https://globalgoals.goldstandard.org/432_cdr_carbon-sequestration-through-accelerated-carbonation-of-concrete-aggregate/



CO₂ liquefaction

A raw gas rich in CO₂ (dry gas composition > 99% CO₂) enters the liquefaction. It is compressed to about 15 bars, dried, and cooled such that a liquid CO₂ phase condenses. The liquid phase is collected and pumped into a vacuum-insulated CO₂ storage tank. The plant only requires electricity and raw gas. We measure the electricity consumption (EC_{liq}) and the amount of liquid CO₂ ($m_{CO_2,l}$) pumped to the CO₂ storage tank.

CO₂ transport

The mass of the CO₂ tank is measured on a truck balance (FR_{CO_2}) as soon as it leaves Ara Region Bern. The type of truck (e.g., EURO 6) and fuel (Diesel or Biogas) is known for calculating transport-related GHG emissions and other environmental impacts. Thus, the generic emission factor for such a vehicle type is known (EF_{tr}). Moreover, the distance (D_{CO_2}) can be calculated according to a conventional routing service.

CO₂ Mineralization

The CO₂ is pumped into the vacuum-insulated CO₂ storage tank at the concrete recycling plant. The liquid level in the tank is monitored. The tank is connected to a reboiler, controlled by the process control located in a process control cabinet. The overall¹¹ electricity consumption (EC_{carb}) is measured. Two pipes guide the gaseous CO₂ to the carbonation silo ($m_{CO_2,1}$) or the mixing water carbonation technology ($m_{CO_2,2}$), measuring the respective mass flows.

Operation of the carbonation silo

A mass flow meter measures the gas flow to the silo ($m_{CO_2,1}$). The silo is filled from the top with concrete aggregate and sealed at the bottom. Since CO₂ is heavier than air, it fills up the silo from the bottom (equivalent to water) and replaces the air, exiting at the top of the silo. Sensors indicate when the CO₂ front reaches the top of the silo. The CO₂ injection is controlled so it does not overflow at the top of the silo.

Quantifying the CO₂ which has been converted to CaCO₃

The presented system allows us to quantify the CO₂ uptake of the concrete aggregate indirectly. This works as follows: Initially, the system is filled with concrete aggregate and air. 1 m³ of silo volume contains about 1500 kg of concrete aggregate¹² (occupying about 700L) and 300 L of air. When CO₂ is injected, it can remain in the system as a gas, absorbed in the liquid phase, or transformed into the solid CaCO₃.

¹¹ Components which require electricity: Liquid CO₂ pump, CO₂ reboiler, power cabinet, PLC, sensors and actuators.

¹² The bulk density of the material will be measured once according to the norm by an accredited concrete laboratory.



CO₂ in gas phase

As it enters the system, it first replaces the air, which is present in between the particles. The ideal gas law allows us to calculate the amount of CO₂ present in a 300 L volume as follows:

$$m_{CO_2}^{gas} = \frac{100000 \text{ Pa} * 0.3 \text{ m}^3}{8.314 \frac{\text{J}}{\text{mol K}} * 293\text{K}} * 0.044 \frac{\text{kg CO}_2}{\text{mol}} = 0.542 \text{ kg CO}_2$$

CO₂ in liquid phase

Concrete aggregate contains about 50 L of water per ton of dry material¹³, depending on its particle size. As a result, part of the CO₂ absorbs in the pore water contained in the concrete aggregate. The amount of CO₂ that effectively absorbs into the pore solution depends on the CO₂ partial pressure in the gas phase (maximum partial pressure is 1 bar) and the solubility of CaCO₃ (thus, how many CO₂ molecules can co-exist with Ca molecules without forming a solid phase). To perform this calculation, we make use of a geochemical equilibrium package. Introducing such a package is out of scope¹⁴ (Johannes Tiefenthaler can share publications where such a model is explained). Figure 2 visualizes the amount of CO₂ in grams per liter of water at a CO₂ partial pressure of 1 bar and as a function of temperature. This corresponds to the high estimate of the CO₂ uptake – and can only be reached if the concrete aggregate is wholly carbonated. However, since the process is diffusion-limited, i.e., the CO₂ needs a lot of time to diffuse through the pore network to reach the inner parts of the particle, the actual amount of CO₂ contained in the pore water is much lower.

Moreover, when CO₂ reaches pores where the cement phases are not carbonated, it precipitates as CaCO₃. For this reason, CO₂ can only be present in the carbonated fraction of the particle. Thus, the exact amount can be approximated as follows:

$$m_{CO_2}^{diss} = m_{H_2O} \times x_{carb} \times c_{CO_2}^{sat}$$

$m_{CO_2}^{diss}$: total amount of CO₂ dissolved in water [kg CO₂]

m_{H_2O} : total amount of water contained in aggregate [kg H₂O]

x_{carb} : extent of carbonation [–]

$c_{CO_2}^{sat}$: apparent CO₂ concentration in pore water at vapor – liquid equilibrium [kg CO₂ per kg H₂O]

Typically, the liquid phase of concrete aggregate (50 L of water at 20°C) can theoretically hold 225 g CO₂ per m³ of aggregate. However, considering the extent of carbonation is conventionally 20 – 50%, the liquid phase usually contains about 50 to 120 g of CO₂ m³ of aggregate. 1 m³ of concrete aggregate can hold about 600 - 750 g of CO₂ in the gas and liquid phases. As a result, it is assumed that all CO₂ fed to the system exceeding this value is transferred to the solid phase and thus fixed permanently.

¹³ The water content of the material will be measured according to the norm (Kernfeuchte).

¹⁴ Wolery, T. EQ3/6 - Software for Geochemical Modeling Version 8.0, UCRL-CODE-2003-009. Lawrence Livermore National Laboratory, Livermore, California **2002** (cit. on pp. 85, 87, 88).



Moreover, the system is designed and controlled so that no CO₂ is overflowing or through other ways exiting the silo.

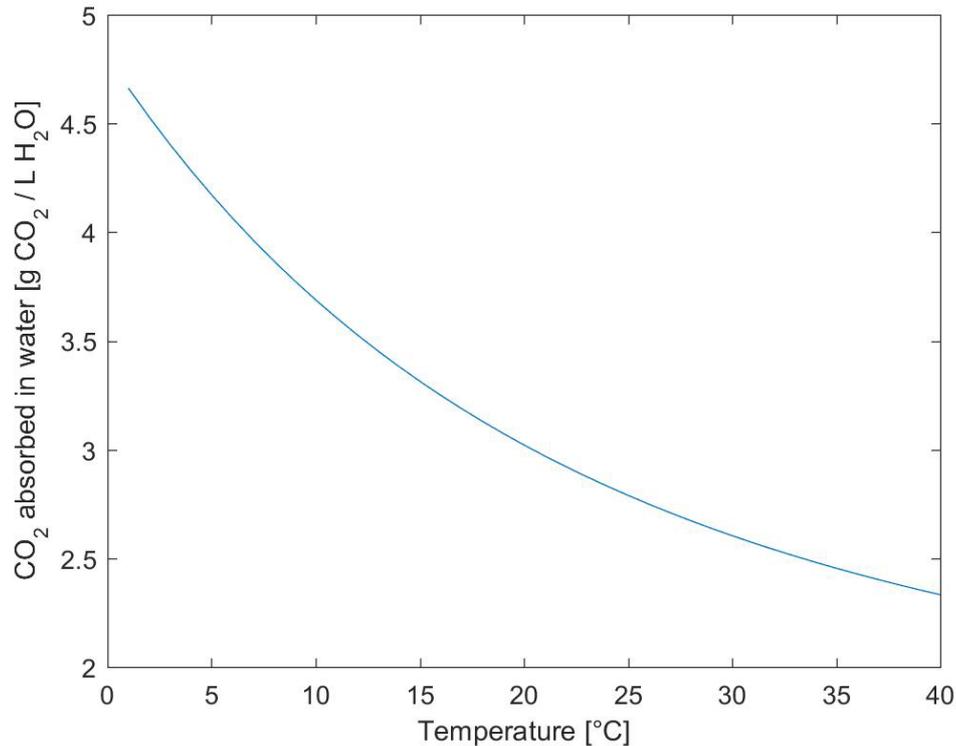


Figure 7. The amount of CO₂ absorbed in the aqueous pore solution at saturated conditions with respect to the solid calcite is plotted as a function of temperature.

Calculating the CO₂ loss

The CO₂ loss corresponds to the amount of CO₂ which exits the system without being permanently stored. Here, we make the following assumption to estimate the upper bound of the loss (conservative estimate):

- As 1 m³ dry aggregate exits the silo system, 75 L of surface and pore water containing the amount of CO₂ shown in Figure 1 are leaving the silo as well. Due to the lower CO₂ partial pressure of the atmosphere, the CO₂ slowly gasses off and enters the environment.
- As 1 m³ dry aggregates exit the silo system, they drag 300 L of pure CO₂ with them, which escapes to the atmosphere.

Typically, concrete aggregate stores about 15 kg CO₂ per m³ – whereas the maximal loss is 750 g CO₂. Thus, the maximal CO₂ loss is about 5%.

Moreover, several features reduce the CO₂ loss even further. First, some air is contained in the silo, which lowers the CO₂ concentration. Moreover, neustark will assess if air injection, just before the silo opens, can decrease the CO₂ concentration of the gas phase exiting with the material. We expect to



reduce the loss down to 20-30%. In addition, when the carbonated concrete aggregate enters the concrete batching system, new cement is added, drastically increasing the pH. As a result, all CO₂ contained in the surface and pore water transform immediately into CaCO₃.

Operation of the Mixing Water Carbonation technology

The concrete plant has an open basin (about 100 m³) where they collect spent water mainly obtained from washing concrete trucks and concrete batching systems. This contains hydrated cement phases – recycled as an inert filler to the concrete mix design. This technology aims to carbonate these hydrated cement phases – and thus to exploit them for CO₂ storage.

The technology investigated takes concrete mixing water (saturated in hydrated cement phases) from the basin (pH~12-13), contacts it with gaseous CO₂ in a static mixer, and returns it to the basin. In this procedure, CO₂ is absorbed into the liquid phase and reacts with the present calcium ions to form CaCO₃. The removal of calcium ions reduces the pH of the solution. Thus, the solution gets undersaturated with respect to the cement phases, which triggers their further dissolution (the extraction of more calcium). This buffering effect (extraction of more calcium) keeps the pH of the solution in the basin relatively constant. As soon as the pH drops below 9.5, the buffering capacity is fully consumed, and the additional CO₂ added is no longer mineralized. The process is stopped until the pH increases again (since new trucks are washed). This process consumes electricity for pumping the suspension through the static mixer. At any time during the process, new water may enter the basin, and water may be extracted to batch concrete.

Experimental methods concrete material tests (Task 2)

In Module 1, RCA and recycling slurry were carbonated with 100 % CO₂ in barrels. RCA was carbonated at different moisture levels to assess the influence of water content on the carbonation behavior. Additionally, RCA's density and water absorption were determined in the uncarbonated and carbonated stages. The microstructure of the carbonated RCA and dried slurries were analyzed with a scanning electron microscope and energy-dispersive X-ray spectroscopy to detect the carbonation-induced changes. The uncarbonated and the carbonated slurries were further studied using thermogravimetric analysis, X-ray diffraction, isothermal calorimetry, and ion chromatography. The impact of RCA and slurries added to mortars was studied following compressive strength development.

In module 2, the experiments were up-scaled to concrete production, measuring workability (concrete flow) as a function of time after mixing and compressive strength to quantify the impact of both slurries and RCA.



Life Cycle Assessment (LCA) (Task 4):

The quantification of environmental burdens along the entire value chain of mineral carbonation of recycled concrete aggregates (RCA) and concrete mixing water is generally based on environmental LCA¹⁵. We performed current and prospective¹⁶ attributional LCA to consider expected developments regarding the value chains in the focus of this WP2 of the DemoUpCARMA research project and the economic system in which they are embedded. The prospective analysis is required since the value chains in focus are still at the research and development stage and will only be implemented at scale in several years. Different development trajectories for the Swiss energy system and the global economy representing specific climate policies as specified in the Swiss Energy Perspectives 2050+ and at the global level (from corresponding Integrated Assessment Models (IAM) scenarios) are taken into account. They are considered to evaluate potentially associated effects on the LCA results.

Figure 8 schematically shows the LCA process model for the concrete carbonation value chain. We assume the value chain is implemented in Switzerland, and we perform an LCA representing current and expected developments up to the year 2050. The value chain includes capturing and supplying CO₂ from various potential sources, its liquefaction, transport, and evaporation before use for mineralization, the supply of RCA, and using the mineralized aggregate for concrete production. The environmental performance of concrete production using carbonated RCA is thus compared to an equivalent production route using non-carbonated RCA and virgin aggregates. Furthermore, the environmental impact of removing CO₂ via its permanent storage in recycling concrete is assessed.

¹⁵ Hauschild, M., Rosenbaum, R., Irving Olsen, S. (2018). Life Cycle Assessment – Theory and Practice. Springer.

¹⁶ Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G. (2022). PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective Life Cycle Assessment using Integrated Assessment Models. Renewable and Sustainable Energy Reviews, doi: 10.1016/j.rser.2022.112311.

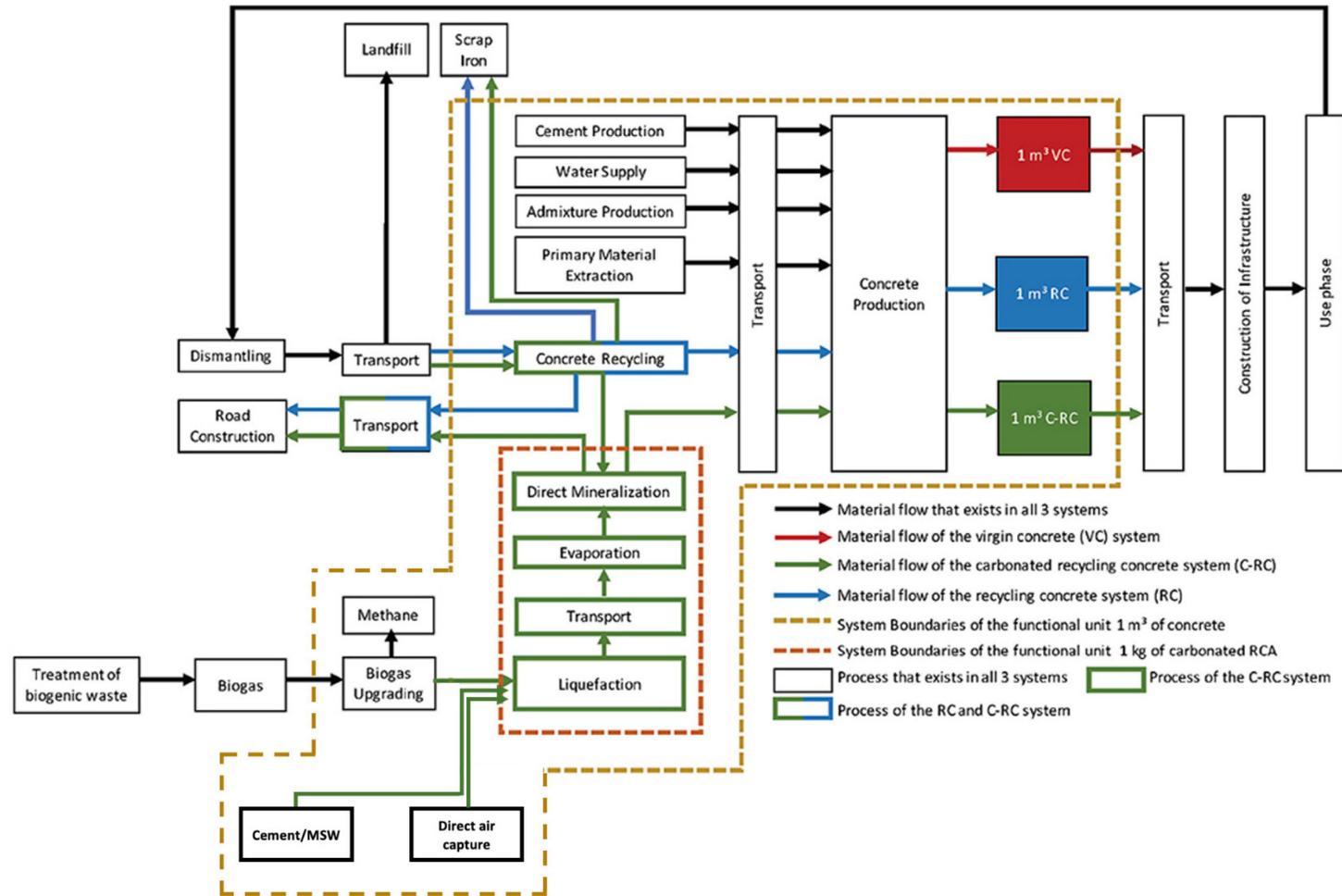


Figure 8. Process scheme representing the parameterized LCA model of the concrete carbonation value chain. Adapted based on our previous analysis¹³.



Life Cycle Inventories (LCI) for the processes directly involved in the carbonation of RCA and carbonated slurry are based on direct information from neustark and other project partners and reflect (for the time being) the current status. The ecoinvent database, version v3.9, system model “allocation, cut-off by classification”¹⁷ is used as a source of background LCI for the impact assessment of today’s supply chain performance. For prospective analyses (up to 2050), we use the Python library *premise*¹⁸ to modify the ecoinvent LCA database and integrate projections relating to electricity, steel, cement, and transport sectors based on global SSP2 reference IPCC scenarios, complemented with Switzerland-specific Energy Perspectives 2050+ Business-As-Usual and (net) ZERO scenarios (i.e., specifically for the electricity mix). It is worth noting that the LCA work conducted within WP3 relies on the ecoinvent database v.3.8. However, comparing the impacts of prominent processes in the system under analysis in ecoinvent v.3.8 and v.3.9 (i.e., cement CEM II/A production, mainly), it is concluded that the differing database versions do not affect the comparability of results between the value chains in WP2 and WP3.

Similar to the work conducted in WP3, impacts on climate are quantified over a 100-year time horizon based on the Global Warming Potential of greenhouse gases using the characterization factors defined by the IPCC AR6 and implemented in ecoinvent v.3.9. Further environmental burdens are quantified using indicators defined in the Environmental Footprint (EF) method v.3.0 as implemented in ecoinvent 3.9 and also used in WP3.

The spreadsheet-based LCA tool allows us to evaluate several value chain configurations with varying CO₂ supply sources, electricity mixes, transport distances, CO₂ mineralization time, etc. It is available for download at <https://doi.org/10.5281/zenodo.8369533>. Unitary impacts of ecoinvent activities are not visible in the public version of the tool because of license restrictions. It is, however, possible to access the list of ecoinvent datasets used to model the different activities in the value chain -- see tab “Unitary impacts”.¹⁹

¹⁷ www.ecoinvent.org

¹⁸ <https://github.com/polca/premise>

¹⁹ Questions about its use will be answered by Romain Sacchi, PSI (romain.sacchi@psi.ch)



4 Results and discussion

Task 2: Development of low-carbon footprint concrete mix designs (month 1-24)

Concrete is produced by mixing cement, water and aggregates (sand and gravel). The fresh concrete needs a good fluidity, named "workability", in order to be compactable once cast in a formwork (walls, slabs, etc.). After hardening it is needs to reach the compressive strength class defined by the engineer. For fine-tune its properties organic additions can be added during concrete production: superplasticizers improve the workability, retarders prolong a good workability and slow down early age strength increase and accelerators do the opposite. Mortar (only sand as aggregate) is often used in the preliminary phase of research projects before moving to the more elaborate production of concrete.

In module 1 recycled concrete aggregate and slurries are carbonated. In module 2 part of the natural aggregates (60 mass-%) are replaced by RCA and/or water is replaced with recycling slurry. The impact of these replacements, both in uncarbonated and carbonated form, on the workability and the mechanical properties of recycling concrete (RC)) is investigated. The key findings of module 1 are that both recycling slurry and RCA are suitable materials for CO₂ absorption. The key findings of module 2 are that the use of recycling slurry and RCA can impact the concrete properties negatively and positively. The use of recycling slurry negatively impacts workability of fresh concrete. However, the effect of the carbonated slurry is less pronounced than the effect of the uncarbonated one. However, the workability can be improved by increasing the dosage of superplasticizer solving this problem. The most important finding is that the carbonated RCA positively impacts concrete quality by improving its compressive strength compared to the use of uncarbonated RCA. This increase in compressive strength provides the opportunity to decrease the cement content in the concrete mix design.

1. The carbonation of recycling slurry containing suspended cement hydrates with 100 % CO₂ results in about 120 g of absorbed CO₂ per 1 kg of dry material (Figure 9). The carbonation alters the composition of both the solids and the liquid phase. The cement hydrates, initially present as suspension, are transformed into CaCO₃ and decalcified calcium-silicate-hydrate (C-S-H). The pH of the liquid decreased from ~12.6 to 6.6, with a significant increase in the dissolved sulfate content caused by the formation and ensuing dissolution of gypsum (calcium sulfate dihydrate) due to carbonation. Using both carbonated and uncarbonated slurry accelerates cement hydration, leading to a higher compressive strength of mortar and concrete for up to 28 days when combined with natural aggregates as shown for mortar mixtures (Figure 10). However, using slurry causes a faster loss of workability of the fresh concrete produced with natural aggregates, which is more pronounced in the case of the uncarbonated slurry. This effect can be overcome by an increase of the added superplasticizer in the concrete mix design by a dosage of 0.4-0.8 mass-% of the cement. The increased dosage of superplasticizer is related to an increase in CO₂ emission relative to the cement



of about 1% and is considered in the LCA results presented in this report. When slurry is combined with RCA instead of natural aggregates, no discernible effect on workability and strength development is observed.

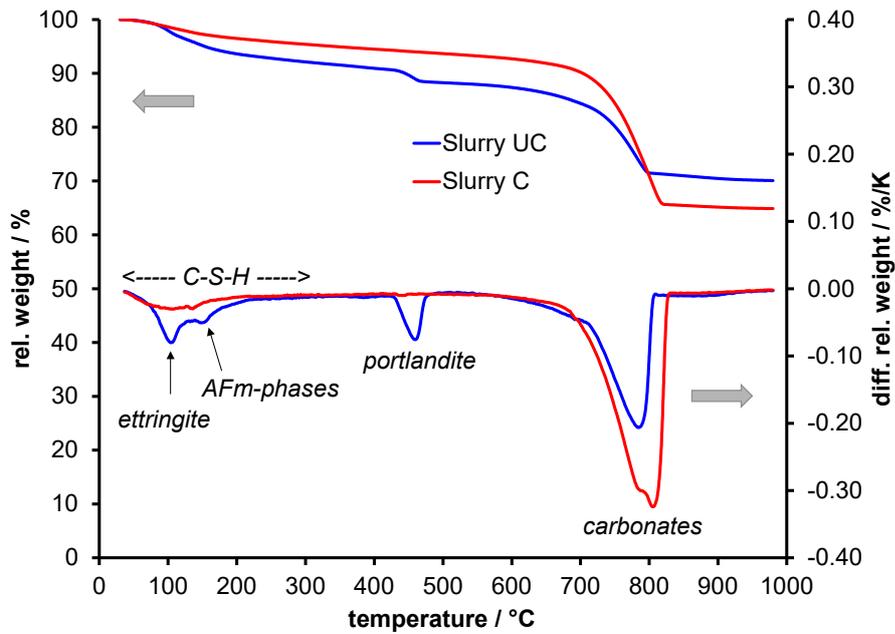


Figure 9. Thermogravimetric analyses of uncarbonated slurry (Slurry UC) and carbonated slurry (Slurry C). The results show that portlandite ($\text{Ca}(\text{OH})_2$), calcium silicate hydrates (C-S-H), and aluminate hydrates such as ettringite and AFm-phases are decomposed. From the contents of carbonates, it was calculated that approximately 120 g of CO_2 can be absorbed by 1 kg of dry concrete slurry.

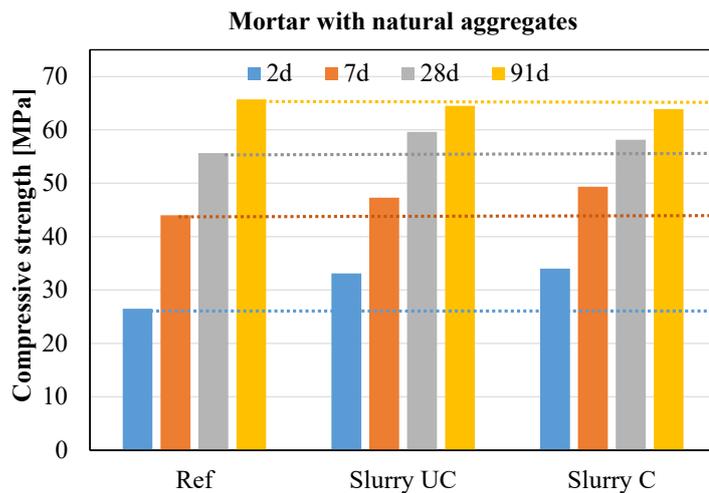


Figure 10. Compressive strength of mortar after 2, 7, 28, and 91 days produced with natural aggregates and tap water (Ref), uncarbonated slurry (Slurry UC), and carbonated slurry (Slurry C).



2. Slurries dried in an oven at 40 °C can be used as mineral addition in cementitious systems. Its reactivity was confirmed on the one hand in experiments on pastes (neither sand nor gravel added), where the dry slurries were blended with cement, and the consumption of calcium hydroxide was monitored by thermogravimetry. However, when used in mortars at a substitution level of cement of 30 mass-%, they considerably decreased the workability of the mixes. This was counteracted by the dosage of superplasticizers in the mortar mix design. As the drying of the slurry results in additional energy consumption, and there is only a slight benefit concerning compressive strength, it currently seems not worthwhile exploring this approach any further.

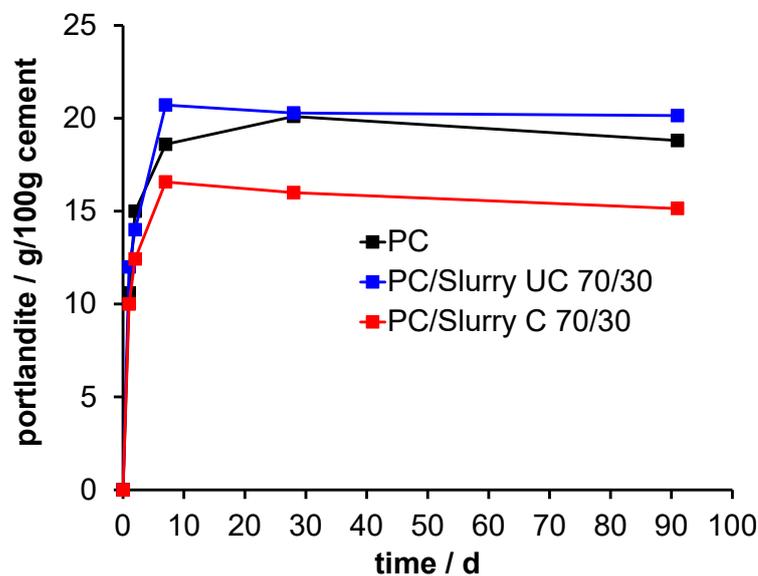


Figure 11. Calcium hydroxide (portlandite) content in hydrated cement pastes at different sample ages referred to 100 g of unhydrated cement.

3. The blend of carbonated slurry (Slurry C) with cement CEM II/A 42.5 N (PC) shows a lower portlandite content than plain PC (Figure 11). This confirms the occurrence of the pozzolanic reaction between the amorphous decalcified C-S-H in the carbonated slurry and portlandite, which leads to the formation of an increased amount of C-S-H, contributing to strength. On the contrary, the mixture with the uncarbonated slurry (Slurry UC) does not consume portlandite hence no increase of strength occurs.
4. The accelerated carbonation of RCA (0-16 mm) using 100 % CO₂ results in about 11 kg CO₂ absorption per ton of dry RCA within 70 minutes (Figure 12). The moisture content of the RCA (60-200 % of total water absorption) has a relatively small effect on the CO₂ uptake. Only in a relatively dry state (30 % of total water absorption), usually not achievable in a concrete plant, does CO₂ absorption of the RCA increase significantly to a value over 20 kg CO₂ per ton of dry RCA (Figure 12).

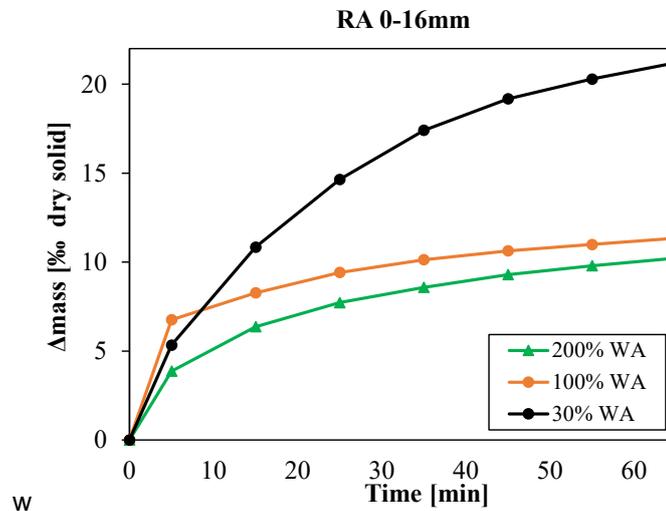


Figure 12. CO₂ absorption of RCA with different moisture contents. Note: The moisture content of the RCA, as delivered by Kästli, was 119 % water adsorption.

5. The microstructural analysis of uncarbonated and carbonated RCA reveals that accelerated carbonation leads to a reaction restricted to thin zones on the surface of the particles. These zones are not continuous but have a patchy distribution (Figure 13). This is likely linked to direct particle-to-particle contacts limiting the accessibility of CO₂. The alteration characteristics in these thin zones resemble an acid attack exhibiting the formation of a calcite layer and a strong decalcification of C-S-H, the main product of cement hydration (Figure 14). The decalcified C-S-H is potentially reactive, as already demonstrated with the dried slurry (Figure 11), and can participate in cement hydration when used as aggregate in new concrete. Compared to mixes with uncarbonated RCA, higher compressive strengths were observed in mortar and concrete mixtures (Figure 15). As such, the carbonation of RCA shows a two-way benefit, the absorption of CO₂ and an increased reactivity potentially allowing a reduction of cement clinker content in new concrete (to be explored in module 3). However, it has to be noted that the increased reactivity of carbonated RCA leads to a faster loss of workability of the fresh concrete. This can be counteracted by using a retarder in the concrete mix design to prolong a good workability and slow down early cement hydration.

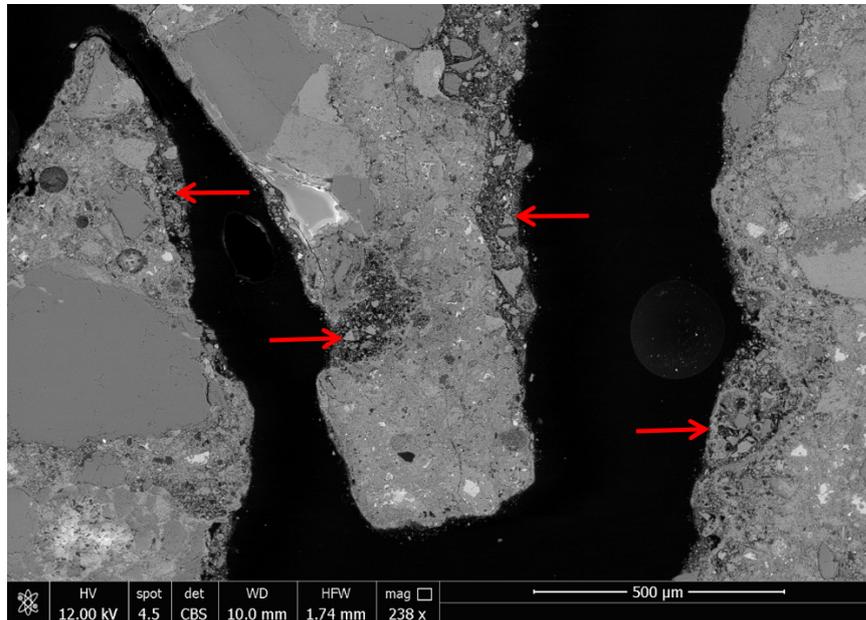


Figure 13. Patchy zones (red arrows) on the surface of RCA show the formation of CaCO_3 and decalcified C-S-H.

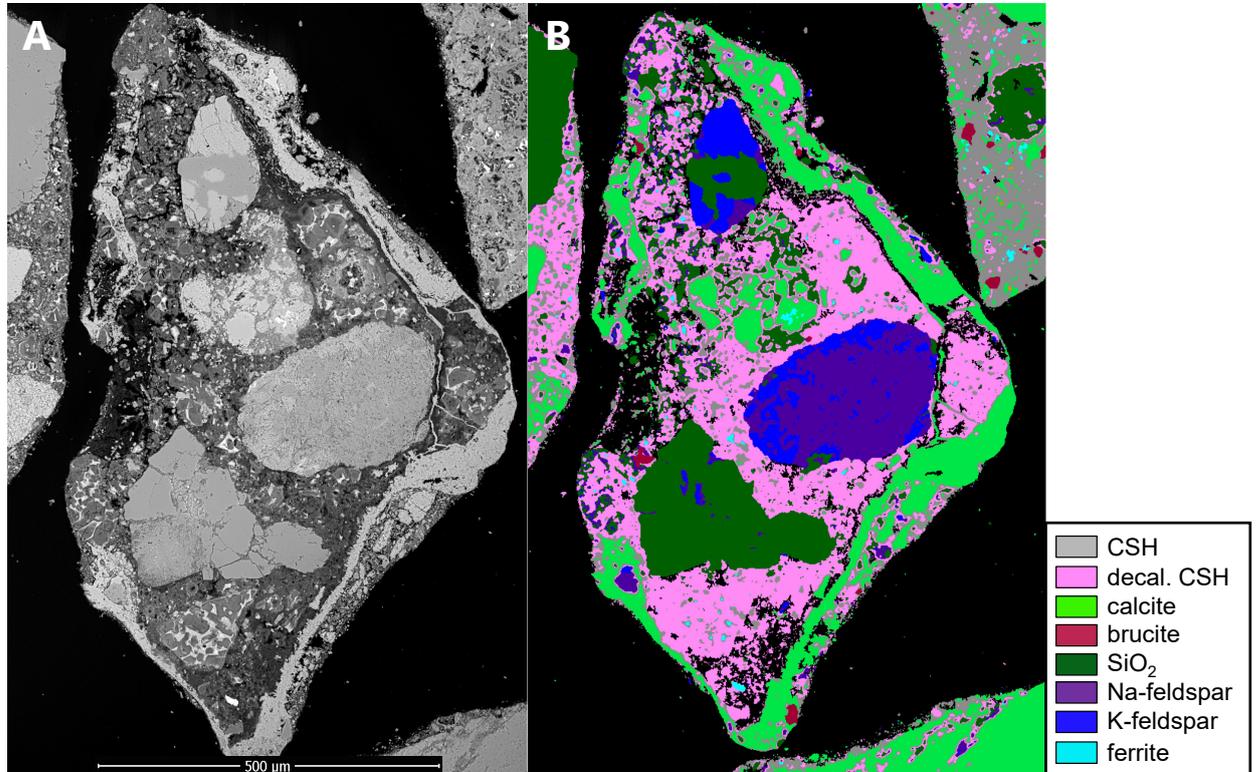


Figure 14. RCA sand particle after carbonation with 100 % CO_2 (A) as BSE-image and as phase map based on element maps showing decalcified C-S-H (pink) and calcite (green) as main alteration products (B).

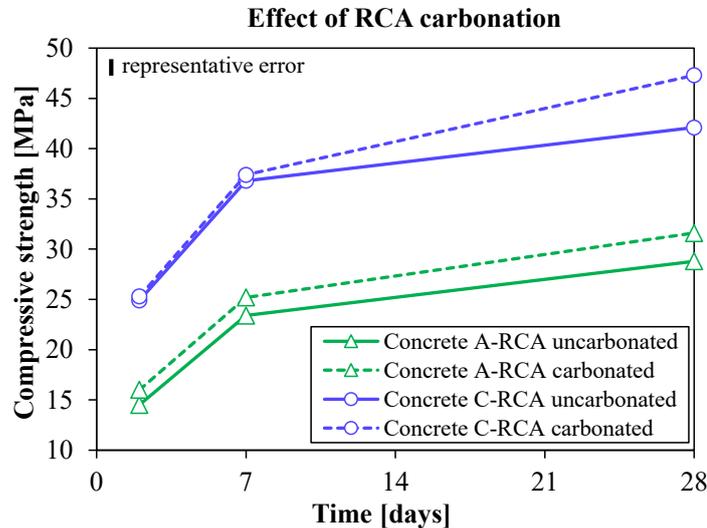


Figure 15. Compressive strength of recycling concrete (type A and type C) containing 60 mass-% of RCA in uncarbonated or carbonated form. The representative error is the standard deviation (± 0.8 MPa) determined on three cubes of 40 different concrete mixtures.

Concrete of type A and C is mainly used in walls and slabs. In concrete slabs, there is a specific risk of developing plastic shrinkage cracks 1-3 hours after casting²⁰ in the case of high air temperature and low relative humidity. Such cracks may reduce the service life of concrete structures due to rebar corrosion, either triggered by carbonation or chloride ingress. To assess the implication of slurry and RCA on plastic shrinkage, three concrete mixtures of type C were produced and tested according to ASTM C 1579-06. Crack analysis performed with digital image correlation²¹ shows that cracking risk increases using (carbonated) RCA compared to primary aggregate (Figure 16). However, using slurry (note: it is uncarbonated) leads to a more pronounced cracking risk. Please note that P-C-tap water and P-C-slurry are two conventional mix designs that are globally used today. R-C-RA carbonated – a new mix design lies in terms of cracking risk just in between the two – while the effect of carbonation was not isolated from the effect of using RA instead of primary aggregate.

The increased cracking risk of concrete slabs containing RCA or slurry in the case of high air temperature and low relative humidity on the construction site can be overcome by covering the concrete surface right after casting to limit drying or by spraying water or a chemical curing agent. These measures are prescribed in the Swiss concrete standard (SIA 262), and it is essential to follow them.

²⁰ Leemann, A., Lura, P. and Loser, R. "Shrinkage and creep of SCC–The influence of paste volume and binder composition." *Construction and Building Materials* 25, no. 5 (2011): 2283-2289.

²¹ Ghourchian, S., Wyrzykowski, M., Lura, P., Shekarchi, M. and Ahmadi, B., 2013. An investigation on the use of zeolite aggregates for internal curing of concrete. *Construction and Building Materials*, 40, pp.135-144.

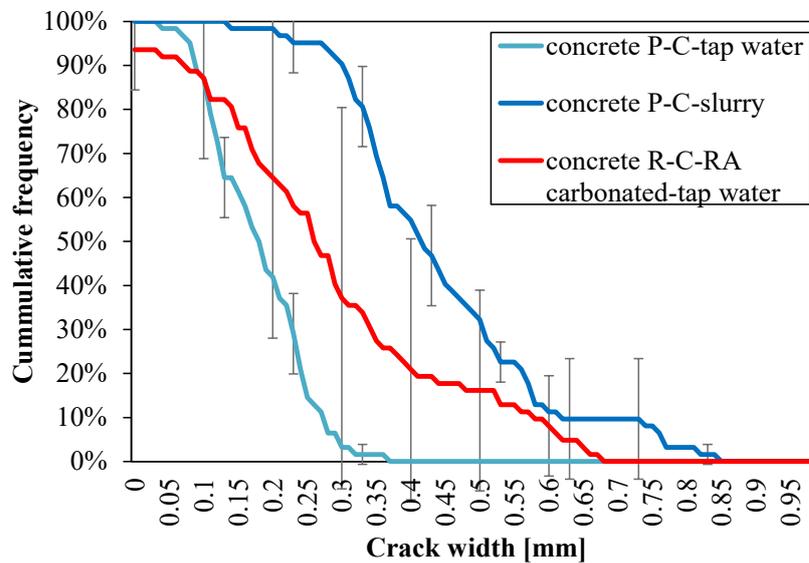


Figure 16. Cumulative crack frequency as a function of crack width of a concrete produced with natural aggregates and tap water (concrete P-C-tap water), a concrete made with natural aggregates and slurry, and a concrete produced with carbonated RA and tap water (concrete R-C-RCA carbonated-tap water). Greater crack width indicates a higher cracking risk. The error bars represent the standard deviation of the crack width as determined on the two samples used to perform the test.

Task 3: Demonstration of the overall value chain (Month 6 – 21)

Carbonation of concrete aggregate:

Two silos, one storing about 40 t of 8/16 mm concrete aggregate and one storing about 150 t of 0/8 mm concrete aggregate, have been equipped with the technology. Since it is a first-of-its-kind plant, an intense ramp-up process started after commissioning. It addressed all identified issues regarding the mechanical installation and piping, the electrics and sensors, and the setting of the process parameters to enable a stable plant operation. Now, these issues are resolved, and the plant shows a specific CO₂ uptake of more than 16 kg of CO₂ per ton of 0/8 mm concrete aggregate within 20 hours of processing and 6 kg of CO₂ per ton of 8/16 mm concrete aggregate within 10 hours of processing. In the RECARB project, a 0/16 mm aggregate was carbonated, composed of 70 wt. % 0/8 mm and 30 wt. % 8/16 mm concrete aggregate. Thus, the 8 kg CO₂ per ton of concrete aggregate in the RECARB project could be increased to 13 kg CO₂ per ton of concrete aggregate – mainly because the plant was designed for longer residence times (e.g., overnight operation). These values are in line with the CO₂ uptake measured in lab-scale experiments. Overall, more than 91 tons of CO₂ have been sequestered.

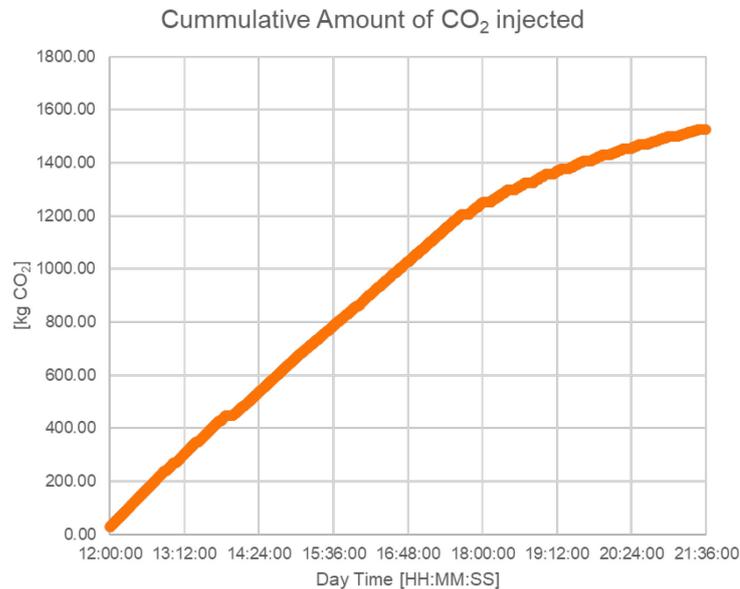


Figure 17. A typical CO₂ injection curve for the 0 to 8 mm containing concrete aggregate silo is shown. Initially, the CO₂ is injected at a constant rate until the CO₂ front arrives at the upper sensors in the silo. At this point, the flow is stepwise reduced, yielding the decay in the CO₂ uptake.

Carbonation of concrete slurry:

The concrete slurry carbonation plant was commissioned next to the collection basin of the concrete slurry. A gas-tight 6 m³ container with a stirrer was connected to the setup. The container was filled with about 4 m³ of concrete slurry from the basin. Over a few hours, the slurry was pumped through the carbonation plant and contacted with CO₂, while the pH of the slurry in the container was monitored. Moreover, the CO₂ concentration in the overhead gas phase of the container was monitored. It was identified, as expected, that the pH dropped from pH 13-14 to pH 9-10 over time. In this period, the CO₂ concentration in the container gas overhead was below ambient, indicating that the CO₂ remained in the slurry and formed CaCO₃.

Moreover, throughout the experiment, the temperature of the slurry increased by about 10°C. As the pH dropped to 8.3, the CO₂ concentration in the overhead increased to 0.5% (= 22 g of CO₂ lost), while about 110 kg of CO₂ was injected and stored. This amounts to about 27 kilograms of CO₂ sequestered per m³ slurry. Values between 24 – 27 kg CO₂ / m³ slurry were obtained in further tests. Overall, about 12,000 kg of CO₂ was sequestered in these trials. Starting in November 2023, the plant will be connected to the slurry basin of Kästli, which will rapidly increase the sequestration rate.

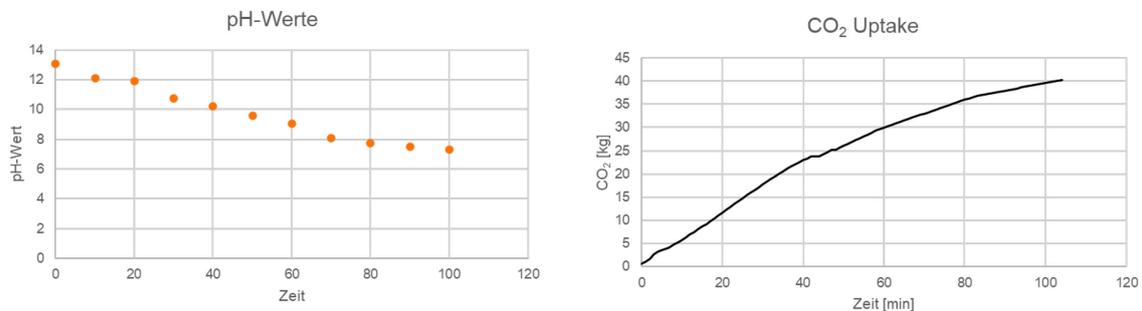


Figure 18. The pH value and the cumulative CO₂ uptake of the slurry of the same experiment are plotted over the process time. It is evident that as more CO₂ is injected, the pH value drops. The CO₂ uptake experiences a saturation.

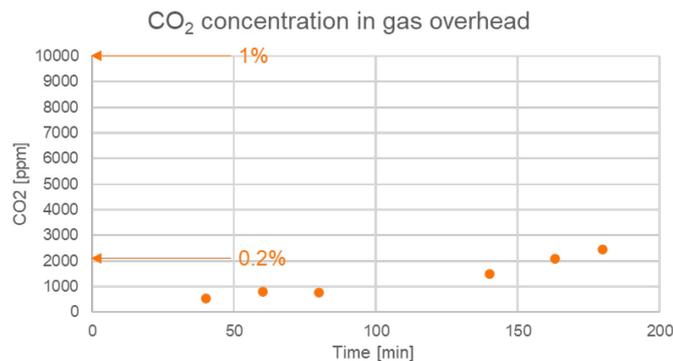


Figure 19. The CO₂ concentration in the gas overhead is visualized over the processing time. For the first 100 minutes, the CO₂ concentration remains at ambient level (1000 ppm is a typical concentration in industrial environments). Afterwards, the concentration slowly increases, reaching very low levels far below 1% of CO₂.

A data monitoring concept has been developed to ensure that the relevant process data required for the LCA and the overall evaluation of the value chain is collected.

Overall, the initial target of fixing 500 t of CO₂ in demolition concrete and slurry was not met for the following reasons:

- Both technologies are first of a kind, and the plant availability was, especially in 2022, relatively low because the many technical and operational learnings were fed back into the plant design by adjusting the plant.
- The construction market was going through a crisis – with a volume decrease of up to 30%.

This led to a much lower CO₂ sequestration throughout the project. Meanwhile, the plants are running in a stable mode – and as soon as the construction market gains momentum again, we are confident that the actual storage rates will lie in the anticipated range.



Task 4: Life Cycle Assessment – evaluation of the environmental performance of the overall value chain (Month 3-24)

1. Parametrized LCA framework

Within the first phase of this project, a parametrized LCA framework for the value chains in the focus of this project has been set up, building on our previous analysis.²² The parameterized LCA model – available as a spreadsheet tool at <https://doi.org/10.5281/zenodo.8369533> – allows for a flexible combination of options for different process steps along the value chain and several scenarios, visualized in Figure 20.

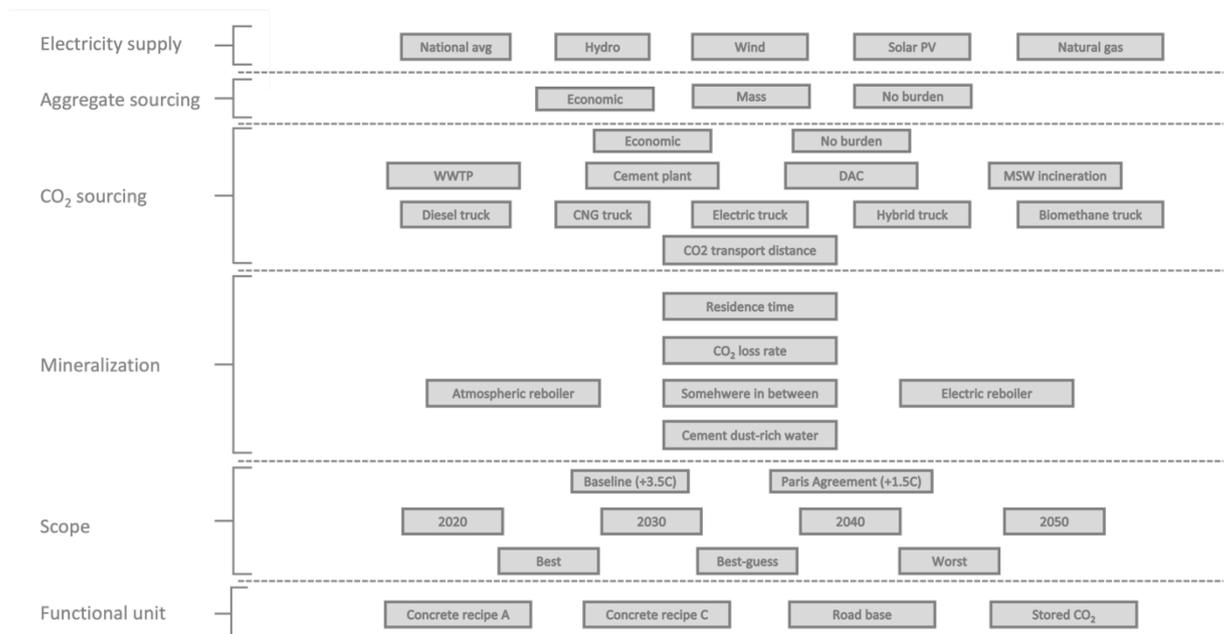


Figure 20. Visualization of the parameter space of the established LCA tool. Different options can be chosen for items listed on the left: electricity supply, allocation of burdens associated with the concrete aggregate source, CO₂ source, mineralization, scope in terms of time and climate scenario, and functional unit. WWTP: Wastewater Treatment Plant; DAC: Direct Air Capture (of CO₂); MSW: Municipal Solid Waste; CNG: Compressed Natural Gas.

Here is a brief description of the different parameters the user can modify:

- The Functional Unit (see *Functional unit* in Figure 20). The tool can calculate the environmental performance of the supply chain for producing:
 1. one cubic meter of concrete (with or without recycled aggregate, with or without carbonation),
 2. one ton of aggregate (carbonated or not) to be used as a road base,

²² Tiefenthaler, J., Braune, L., Bauer, C., Sacchi, R., and Mazzotti, M. (2021). Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector. *Frontiers in Climate*, doi: 10.3389/fclim.2021.729259



3. or simply back-calculate the required carbonated aggregate and other requirements to sequester one ton of CO₂ in concrete (and the associated environmental burdens).
- The concrete mix design (see *Scope* in Figure 20). The user can select the best, average ("best-guess"), and worst-performing concrete mix designs if specified under the "Concrete" tab. Current concrete mix designs are based on EMPA's concrete mix designs, A and C, developed within this WP.
 - The temporal and climate policy related scope (see *Scope* in Figure 20). Several years can be selected, with 2020 corresponding to today's performance. The time step is associated with a "background scenario": "Baseline (+3.5 C)" and "Paris Agreement (+1.5 C)". When the "Baseline (+3.5 C)" is selected together with a future year (i.e., from 2030 on), impacts from global (i.e., non-Swiss) products and services are aligned by *premise*²³ to the projections from the SSP2 scenario from the Integrated Assessment Model REMIND²⁴, while the national electricity mix is based on the Business-As-Usual scenario of the Swiss EP2050+. When "Paris Agreement (<2 C)" is selected, impacts from global products and services are adjusted to the SSP2 – RCP 1.9 (W/m²) scenario from REMIND. At the same time, the national electricity mix is based on EP2050+'s ZERO Basis scenario. The user can also select a specific electricity technology to operate the supply chain (e.g., solar photovoltaics, hydropower, etc.) (see *electricity supply* in Figure 20).
 - The mineralization parameters (see *Mineralization* in Figure 20). The user can opt for the cement-rich slurry in the concrete mix design. Other parameters relating to the mineralization plant can be selected: using an electric or atmospheric reboiler to evaporate the CO₂, the residence time of the aggregate in the CO₂ silo, the CO₂ loss rate, etc. Note that the residence time conditions, the extent to which recycled aggregate can absorb CO₂, based on the latest experimental data regarding CO₂ uptake vs. residence time provided by neustark, have been incorporated. Note that an increased residence time also increases electricity expenditure.
 - The CO₂ sourcing options (see *CO₂ sourcing* in Figure 20). The user can choose between different sources of CO₂. Options for supply of CO₂ for mineralization are: wastewater treatment plants with biogas upgrading (WWTP), direct air capture of CO₂ (DAC), cement plants, and municipal solid waste incineration (MSWI). Note that for all sourcing options, the CO₂ is considered non-fossil. For example, when sourcing CO₂ from a cement plant, the tool assumes the gas originates from the combustion of biomass-rich fuel – leaving the CO₂ of fossil origin non-captured from an emissions accounting viewpoint. This CO₂ can be transported by different types of trucks (electric, diesel, biomethane, natural gas) over user-specified distances.
 - The aggregate sourcing options (see *Aggregate sourcing* in Figure 20). Recycled concrete aggregate can be supplied free of environmental burdens, or the environmental burdens of the supplying process can be allocated according to the mass or economic revenue of the by-products.

²³ <https://github.com/polca/premise>

²⁴ <https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind>



2. Modelling, data, and assumptions

We present the different data, assumptions, and modeling approaches used in the LCA framework. We start with the concrete mix step and describe upstream activities until the sourcing of CO₂.

a. Concrete mixing and mix designs

The concrete mix designs A and C elaborated within this WP are presented in Table 1. In the Base scenario, the results of which are shown further down this section, we compare four options for each mix design: virgin aggregate, recycled concrete aggregate, and recycled carbonated concrete aggregate without and with carbonated slurry.

Table 1 Concrete mix designs A and C. Source: EMPA

Option	Mix designs	Aggregate type	Density	Cement	Gravel	Sand	Recycled aggregate	Recycled carbonated aggregate	Water	Carbonated slurry	Super-plasticizer
			[kg/m ³]	[kg/m ³]	[kg/m ³]	[kg/m ³]					
A.1	Concrete recipe A	Virgin agg.	2180	280	690	1035	n.a.	n.a.	175	n.a.	0
A.2		Recycled agg.	2178	290	279	418	1028	n.a.	163	n.a.	0
A.3		Recycled carbonated agg.	2174	278	279	418	330	702	166	n.a.	0
A.4		Recycled carbonated agg. + carbonated slurry	2174	278	279	418	330	702	n.a.	197	1.60
C.1	Concrete recipe C	Virgin agg.	2204	310	703	1054	n.a.	n.a.	137	n.a.	1.86
C.2		Recycled agg.	2214	320	283	425	1045	n.a.	141	n.a.	1.60
C.3		Recycled carbonated agg.	2201	294	283	425	336	713	150	n.a.	1.60
C.4		Recycled carbonated agg. + carbonated slurry	2201	294	283	425	336	713	n.a.	177	2.20

b. Ancillary inputs

Datasets from the LCA database ecoinvent provide ancillary inputs necessary for concrete mixing. This includes the concrete factory, lubricants, production of concrete waste, electricity, diesel, fuel oil, and heat from natural gas. We also consider the transport of these inputs (primarily by road and rail).

c. Mineralization

To align with the carbonation measurements made by neustark, the size distribution in terms of mass considered is presented in Table 2. It produces an average CO₂ mineralization of 13 kilograms per ton of aggregate for 5 hours, as shown in Table 3. The CO₂ uptake curve as a function of the residence time for each diameter interval is specified under the tab Mineralization in the spreadsheet LCA tool.



Table 2 Default size distribution of recycled concrete aggregate and residence time. Source: neustark

Diameter	mm	0-0.063	0.063-0.125	0.125-0.25	0.25-0.5	0.5-1	1-2	2-4	4-16
Mass distribution	%	2.9	2.1	3.3	5.8	8.1	11.8	15.4	50.6

Table 3 Average carbonation level and residence time of the recycled carbonated aggregate. Source: neustark

CO ₂ capture per ton [kg CO ₂ /t aggregate]	13.7
Residence time [t]	5
Average carbonation level	65%

Energy and material requirements for the CO₂ silo can be consulted under the tab Mineralization of the spreadsheet tool.

d. Evaporation

Pressurized CO₂ can be evaporated into the mineralization silo using an atmospheric or electric re-boiler. In our Base scenario, and as observed in the neustark operations, we consider an atmospheric re-boiler requiring less electricity. The specifications considered for both re-boilers are described in Table 4. Since no detailed material characterization for the reboilers is available, we assume it is entirely made of injection-molded stainless steel parts.

Table 4 Specifications for atmospheric and electric re-boilers. Source: neustark

		Atmospheric reboiler	Electric reboiler
Power output	kW	1.6	20
Output flow rate	kg CO ₂ /h	200	180
Electricity use	kWh/t CO ₂	8	111
Average load factor	%	73%	27%
Average electricity use	kWh/t CO ₂	6	30
Weight	kg	243	243
Material composition		Chromium steel	Chromium steel

e. Liquefaction and transport

The liquefaction plant is sized according to the specifications presented in Table 5. Without a precise bill of materials, we assume it is entirely made of injection-molded stainless-steel parts. We also consider the supply and loss of refrigerant over time. We also consider a 5% gas loss during liquefaction, based on neustark's observations.



Table 5 Specifications of the CO₂ liquefaction plant. Source: neustark

Weight	kg	10,000
Output flow rate	kg/h	270
Load factor		90%
Production	kg CO ₂ , over lifetime	42,573,600
Electricity use	kWh/t liquefied CO ₂	230
Refrigerant use	kg, over the lifetime	165
Refrigerant loss	kg, over the lifetime	55

In the Base scenario, the liquefied gas is transported by a biomethane-fed truck over 20 kilometers. We chose a biomethane-fed vehicle to reflect the existing neustark supply chain in Switzerland, but other types of powertrains can be selected.

f. CO₂ sourcing

In the Base scenario, the production of biogenic CO₂, a co-product from biogas upgrading, does not bear any environmental burden, as the latter is entirely allocated to the supply of biomethane. The sourcing of this CO₂ does, however, entails emissions related to the capture, liquefaction, and transport of the gas, which are accounted for. However, biogenic CO₂ may become a valued product for which a market may be established – which might change how environmental burdens are assigned to such “feedstock” CO₂. Table 6 presents different sourcing options for biogenic CO₂, including CO₂ from a biogas upgrading plant (as is the case today) based on an economic allocation (i.e., where biomethane does not bear the entire environmental burden of the upgrading process and a fraction of burdens is assigned to the biogenic CO₂). The modeled Direct Air Capture configuration uses a high-temperature heat pump, besides a direct input of electricity, to provide the required 5.4 GJ of heat per ton CO₂ captured, with a Coefficient Of Performance of 2.5²⁵. It is important to note that for this LCA the CO₂ is assumed to be entirely biogenic (or atmospheric in case of DAC) for all sourcing options, even when the emitter produces a mix of fossil and biogenic CO₂ (e.g., a cement plant). Such an accounting perspective needs to be verified based on business practices to be established in the future.

²⁵ <https://www.sciencedirect.com/science/article/pii/S0360544218305759>



Table 6 Operational parameters for the different biogenic CO₂ capture and supply options considered. Note that for CO₂ from the biogas upgrading plant, an economic-based allocation is performed (resulting in a burden split of 94% for biomethane and 6% for CO₂) based on a market value of 2.08 CHF/kg²⁶ natural gas (used as a proxy for the biomethane market value) and 0.08 CHF/kg of biogenic CO₂²⁷. Other market prices are considered for ulterior years – see under the Biogas tab in the spreadsheet model. In the base scenario however, CO₂ from the biogas upgrading plant comes without environmental burden as it is considered a waste product.

	Biogas upgrading (economic allocation)	DAC	MSWI	Cement plant	Remark
Inventories source	Ecoinvent 3.9 cut-off	(Qiu et al. 2022) ²⁸	(Bisinella et al. 2021) ²⁹	(Meunier et al. 2020) ³⁰	
Capture technology	Mono-ethanolamine (MDEA)				
CO ₂ concentration in gas [ppm]	~700,000	~418	105,000	204,000	
Heat requirement [GJ/ton CO ₂ captured]	0.217	5.4	3.9, decreased to 2.93 to consider process heat recovery.	3.66, corrected to 2.7 to consider process heat recovery.	In (Meunier et al. 2020), the heat requirement is initially discounted by 26% because it is integrated with a methanol production unit: the heat from the exothermic synthesis can be recovered to sustain the CO ₂ capture process partly.
Electricity requirement [MWh/ton CO ₂ captured]	0.007	0.5	0.1	0.07	
MEA degradation rate [kg/ton CO ₂ captured]	7e-6	3	4	1, corrected to 4	In (Meunier et al. 2020), a flash tank limits MEA loss via water evaporation. However, for a fairer basis of comparison, we align the MEA degradation rate with that of the MSWI case (i.e., 4 kg MEA/ton CO ₂ captured).

g. Aggregate sourcing

In the Base scenario, the RCA comes free of environmental burden (besides those associated to its transport by truck over 25 km), as the process emissions and energy requirements are allocated instead to treating demolition waste and recovering reinforcement steel in old concrete. However, this is an allocation choice, and other approaches may be used. For this reason, we propose considering RCA as a product and allocating a share of the demolition waste treatment process to its supply based on 1)

²⁶ https://fr.globalpetrolprices.com/Switzerland/natural_gas_prices/

²⁷ <https://www.iea.org/data-and-statistics/charts/simplified-levelised-cost-of-competing-low-carbon-technologies-in-long-distance-transport>

²⁸ <https://www.nature.com/articles/s41467-022-31146-1>

²⁹ <https://www.sciencedirect.com/science/article/pii/S0956053X21002440>

³⁰ <https://www.sciencedirect.com/science/article/pii/S0960148119310304>



mass and 2) market value and test the implication of such choice in the Sensitivity Analysis section (see Annex I - Allocation of recycled aggregate). The corresponding allocation factors are presented in Table 7.

Table 7 Mass and market value-based allocation options for treating demolition waste. In the base scenario, recycled concrete aggregate is supplied free of burden. Also, when allocating based on mass, the service of waste treatment is rendered free of environmental burdens.

	Recycled concrete aggregate	Steel reinforcement	Waste treatment
Price [CHF/t]	18.7	77	
Amount [tons/m ³ waste]	0.97	0.02	
Turnover [CHF per m ³ waste]	18.139	1.54	8.86
Economic allocation factor	64%	5%	31%
Mass allocation factor	98%	2%	zero

h. Electricity mixes

In the most optimistic case (i.e., free-of-burden CO₂ and recycled aggregate), the mineralization process still requires about 315 kWh of electricity per ton of stored CO₂. The type of electricity used to operate the supply chain can, therefore, impact the operation's environmental performance. To analyze the current supply chain managed by neustark, we considered the Swiss electricity supply mix defined by the FOEN³¹ for 2018, with a corresponding carbon footprint of 0.135 kg CO₂-eq./kWh at low voltage³². This consumption mix incorporates transboundary electricity trades but excludes electricity purchased via Guarantees of Origin. For ulterior years (until 2050), two electricity scenarios from the Energy Perspective 2050+ report are considered: Business-As-Usual and ZERO Basis, which implementation can be consulted³³. The electricity mixes available in the tool are presented in Table 8.

³¹ <https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/fachinfo-daten/Umweltbilanz-Strommix-Schweiz-2018-v2.01.pdf.download.pdf/Umweltbilanz-Strommix-Schweiz-2018-v2.01.pdf>

³² It was impossible to precisely reproduce the published value of 0.128 kg CO₂-eq./kWh, as the underlying LCA database differs.

³³ <https://github.com/premise-community-scenarios/energy-perspective-2050-switzerland>



Table 8 Swiss national consumption electricity mix per scenario and time step. The last column represents the greenhouse gas emissions per kilowatt hour of electricity supplied to the consumer. For 2020, the consumption mix is based on the latest FOEN assessment.

Background scenario	Year	Hydro	Nuclear	Natural gas	Solar	Wind	Biomass	Coal	Oil	Waste	Imports	Grid loss	Climate impacts, kg CO ₂ eq per kWh
Baseline (+3.5C)	2020	66.0%	17.3%	0.7%	4.0%	3.2%	0.3%	1.0%	0.0%	1.3%	6%	6.5%	0.135
Baseline (+3.5C)	2030	59.1%	11.3%	5.5%	11.2%	5.9%	1.8%	1.7%	0.0%	3.5%	0%	6.5%	0.051
Baseline (+3.5C)	2040	58.3%	3.4%	8.4%	15.3%	7.5%	1.9%	1.1%	0.0%	4.1%	0%	6.5%	0.054
Baseline (+3.5C)	2050	54.9%	0.2%	8.0%	20.8%	10.7%	1.7%	0.0%	0.0%	3.8%	0%	6.5%	0.040
Paris Agreement (<2+C)	2020	69.1%	20.0%	1.7%	3.7%	2.1%	2.6%	0.7%	0.1%	0.0%	0%	6.5%	0.135
Paris Agreement (<2+C)	2030	57.4%	14.7%	3.1%	14.3%	5.7%	0.4%	1.4%	0.0%	3.0%	0%	6.5%	0.040
Paris Agreement (<2+C)	2040	57.0%	0.3%	2.3%	30.7%	6.4%	0.9%	0.0%	0.0%	2.5%	0%	6.5%	0.020
Paris Agreement (<2+C)	2050	50.9%	0.0%	1.0%	40.6%	4.9%	0.6%	0.0%	0.0%	2.0%	0%	6.5%	0.014

3. Base scenario: comparing concrete mix designs A and C

Table 9 shows the model parameters for our Base scenario, comparing virgin aggregate, recycled aggregate, and carbonated recycled aggregate to produce one ton of concrete. A simplified representation of the system boundaries of the three supply chains is also shown in Figure 21. The biogenic CO₂ is supplied with a high degree of purity by a biogas upgrading plant and is environmentally burden-free – besides the operational expenditures to capture, liquefy, and transport it. The supply distance to the mineralization plant is assumed to be 20 kilometers, operated by an EURO-6 biomethane-fed truck. The CO₂ is evaporated using an atmospheric reboiler, and the overall loss up until the aggregate extraction from the silo is 5%³⁴. We consider a residence time for the aggregate in the CO₂ silo of 5 hours (i.e., 13 kilograms of CO₂ sequestered per ton of recycled aggregate). The fourth and eighth options (i.e., A.4 and C.4) use carbonated slurry in the mix designs A and C. The concrete mix designs A and C considered in the tool and developed by EMPA are described in Table 1.

³⁴ Loss estimated by neustark.

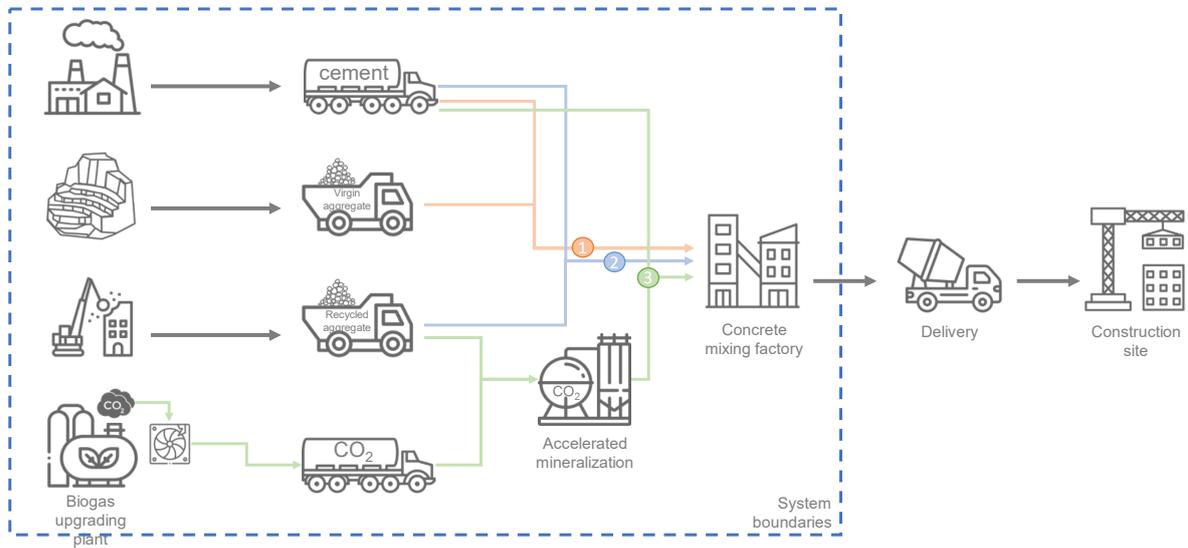


Figure 21. System boundaries of the three pathways considered: concrete production with 1) cement + virgin aggregate (orange arrows), 2) cement + recycled aggregate (blue arrows), and 3) cement + recycled carbonated aggregate (green arrows). Delivery and use of concrete are out of scope. While all relevant activities and services are considered, they are not all represented in this figure (e.g., provision of electricity).



Table 9 Main model parameters for comparing the use of carbonated recycled aggregate to virgin aggregate

	Options		A.1	A.2	A.3	A.4	C.1	C.2	C.3	C.4
	Mix design		Concrete mix design A				Concrete mix design C			
	Year		2020							
CO ₂ supply parameters	CO ₂ source		WWTP							
	CO ₂ burden allocation		No burden							
	CO ₂ transport to mineralization plant	km	0							
	CO ₂ loss rate	%	5							
	Reboiler		Atmospheric							
	Fuel for CO ₂ transport truck		Road (biomethane)							
Aggregate supply parameters	Aggregate type		Virgin agg.	Recycled agg.	Recycled carbonated agg.	Recycled carbonated agg. + carbonated slurry	Virgin agg.	Recycled agg.	Recycled carbonated agg.	Recycled carbonated agg. + carbonated slurry
	Recycled aggregate burden allocation		No burden							
Mineralization plant parameters	Use of water containing carbonated cement dust?	bool	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE
	Annual output	tons	30,000							
	Electricity mix		National							
	Lifetime of infrastructure	years	5							
	Residence time	hours	5 (~13 kg CO ₂ stored per ton aggregate)							

a. Carbon dioxide removal and GHG emissions mitigation

Table 10 There are two prominent and simultaneous effects when using carbonated RCA: 1) the permanent storage of CO₂ in RCA and 2) the reduction of GHG emissions because of the reduced need for natural aggregates and cement. To that effect, we assess the different use cases with respect to two indicators:

- 1) CO₂ removal efficiency: *the amount of GHG directly and indirectly emitted per ton of CO₂ permanently removed from the atmosphere.* Referring to Table 10, column A.3 or A.4, it is calculated as the sum of GHG emissions, in kilograms, related to “Mineralization”, “Evaporation”, “Transport”, “Liquefaction”, and “CO₂ supply”, divided by the amount, in kilograms, of CO₂ stored in the RCA, or:

$$\frac{\alpha + \beta + \gamma + \delta + \varepsilon}{-\theta} \times 1000$$



With:

- α GHG emissions associated with cement mineralization,
- β GHG emissions associated with the evaporation of CO₂,
- γ GHG emissions associated with the transport of CO₂,
- δ GHG emissions associated with the liquefaction of CO₂,
- ε GHG emissions associated with the production of CO₂,
- θ amount of CO₂ stored in the RCA.

2) GHG mitigation efficiency: *the amount of GHG directly and indirectly emitted with respect to the sum of a) CO₂ permanently removed from the atmosphere and b) avoided GHG emissions.* Referring to Table 10, columns A.1 and A.3 or A.4, it is calculated as the sum of GHG emissions related to “Mineralization”, “Evaporation”, “Transport”, “Liquefaction”, and “CO₂ supply”, divided by the sum of a) CO₂ stored in the RCA and b) the change in GHG emissions relating to “Cement”, “Nat. Aggregates”, “Aggregate recycling”, and “Others (concrete)” of the scenario using carbonated RCA relative to the counter-factual scenario or:

$$\frac{\alpha_c + \beta_c + \gamma_c + \delta_c + \varepsilon_c}{(\lambda_c + \mu_c + \nu_c + o_c) - (\lambda_r + \mu_r + \nu_r + o_r) - \theta_c} \times 1000$$

With:

- Subscripts r and c denoting the mineralization and counter-factual scenarios, respectively,
- λ GHG emissions associated with the production of cement,
- μ GHG emissions associated with the production of natural aggregate,
- ν GHG emissions associated with the supply and transport of raw materials for concrete production (except cement and natural aggregate),
- o GHG emissions associated with the supply of RCA.

GHG emissions are characterized using the factors provided in the sixth assessment report of the IPCC for a time horizon of 100 years³⁵. Table 10 shows the GHG emissions for the mix designs A and C, using virgin (A.1, C.1), RCA (A.2, C.2), carbonated RCA (A.3, C.3), and carbonated RCA with carbonated slurry (A.4, C.4). When using carbonated slurry in addition to carbonated RCA, the CO₂ removal efficiency is about 95% (or 50 kg CO₂-eq. emitted per ton of biogenic CO₂ removed from the atmosphere) for both mix designs. It decreases by a percentage point when not using carbonated

³⁵ https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SummaryVolume.pdf



slurry (i.e., 94%). The most contributing steps in the mineralization value chain are the CO₂ liquefaction and the mineralization steps, representing 93% of the GHG emitted per ton of biogenic CO₂ captured and stored in RCA. Figure 22 graphically decomposes the contribution of each step in the mineralization value chain per ton of biogenic CO₂ captured. In general, CO₂ emissions are almost entirely responsible for climate impacts of the investigated value chains – i.e., emissions of other greenhouse gases such as CH₄ or N₂O are negligible.

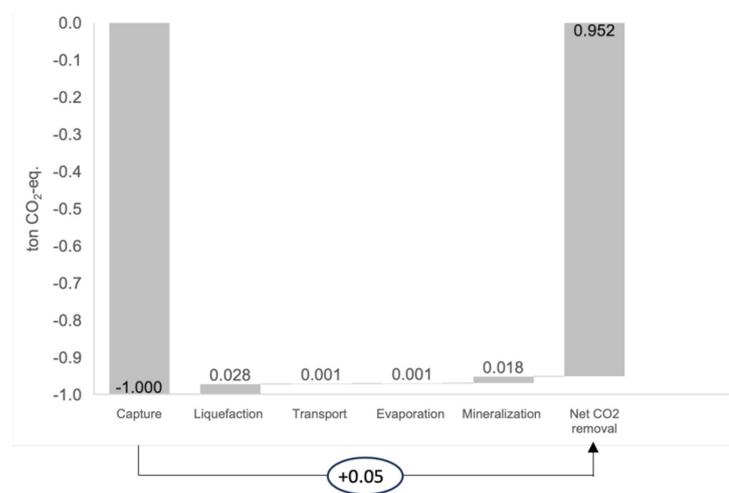
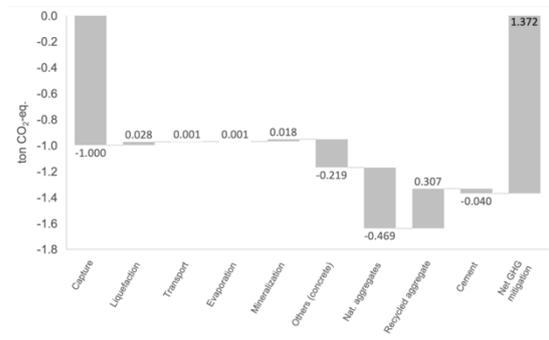
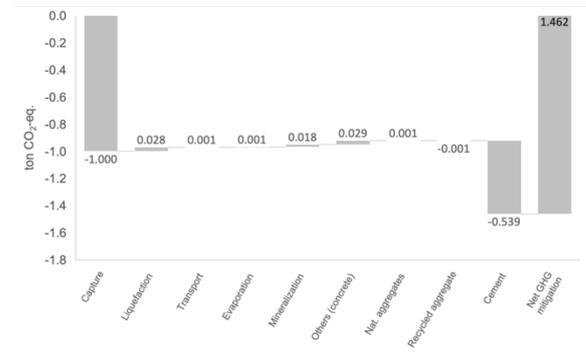


Figure 22: Amount of GHG emissions per ton of CO₂ captured via carbonation of RCA and use of carbonated slurry. The “CO₂ removal efficiency” here is ca. 95%, as 48 kg CO₂-eq. (rounded: 0.05 tons) are emitted per ton of CO₂ captured. “Net CO₂ removal” corresponds to the amount of CO₂ removed from the atmosphere after GHG emissions (in kg CO₂-eq.) occurring throughout the different steps of the mineralization value chain are subtracted.

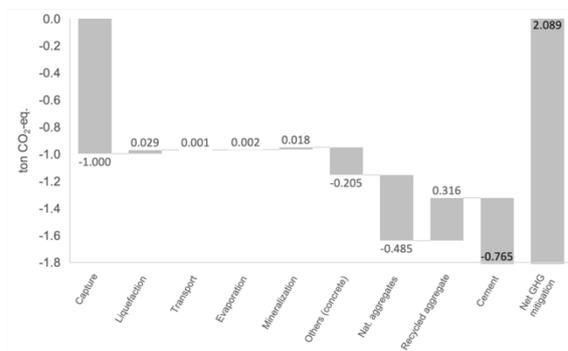
In terms of GHG emissions mitigation, the use of carbonated RCA and carbonated slurry leads to a GHG emissions reduction beyond the removal of biogenic CO₂ from the atmosphere, with respect to mix designs using virgin aggregate or (uncarbonated) RCA, as shown in Table 10 and illustrated in Figure 23. Concerning the use of virgin aggregate (A.4 vs. A.1 and C.4 vs. C.1), the use of carbonated RCA with carbonated slurry allows reducing GHG emissions related to producing and transporting virgin aggregates (although partly compensated by the transport of RCA), as well as the notable reduction of GHG emissions due to a reduced cement used in mix design C (i.e., 294 kg cement CEM II/A per m³ concrete C, against 310 kg when using virgin aggregates only). Concerning the use of (uncarbonated) RCA (A.4 vs. A.2 and C.4 vs. C.2), the use of carbonated RCA with carbonated slurry allows for reducing GHG emissions related to cement production mainly, thanks to the formation of calcium silicate hydrates (C-S-H). The benefits in terms of GHG emissions reduction from reduced cement use are more pronounced for mix design C. In fact, for every ton of biogenic CO₂ captured and stored in RCA, an equivalent amount of GHG emissions is reduced along the concrete production chain.



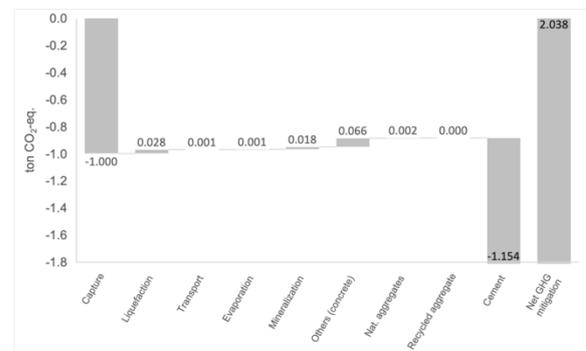
a) A.4 relative to A.1



b) A.4 relative to A.2



c) C.4 relative to C.1



d) C.4 relative to C.2

Figure 23: Change in GHG emissions per ton of CO₂ captured via carbonation of RCA and use of carbonated slurry relative to the mix design that does not use carbonated RCA. “Net GHG mitigation” corresponds to the amount of CO₂ removed from the atmosphere and the sum of changes in GHG emissions (in kg CO₂-eq.) (equivalent to mitigation of GHG emissions) occurring throughout the different steps of the value chain, relative to the mix design not using carbonated RCA. Interpretation of case a): Each ton of biogenic CO₂ captured from the biogas upgrading plant leads to removing $1 - (0.028 + 0.001 + 0.001 + 0.018) \sim 0.95$ ton of CO₂-eq. from the atmosphere, as well as further reducing GHG emissions by 0.42 tons of CO₂-eq. (0.219 t and 0.469 t from avoided natural aggregate sourcing and transport, -0.307 t caused by recycled aggregate transport and 0.04 t from reduced cement use), for a total GHG emissions mitigation of 1.372 tons of CO₂-eq.

Several sensitivity analyses are conducted to test the robustness of the results on the choice of CO₂ sourcing option, residence time of RCA in the mineralization chamber, carbon intensity of electricity, allocation choice for RCA sourcing, type of reboiler, and carbon intensity of background activities. We refer the reader to the Annex I section of this document for more details. The results are summarized in the Discussion section.



Table 10 **Global Warming Impacts** over a 100-year time horizon disaggregated into contributions from specific process steps along the value chain, in *kilograms of CO₂-eq. for one-ton concrete* of both concrete mix designs A and C, using virgin (A.1, C.1), recycled (A.2, C.2), and carbonated concrete aggregate (A.3, C.3), with the optional use of carbonated slurry (A.4, C.4). Option numbers (e.g., A.1, etc.) correspond to the specifications in Table 1. Green-shaded cells represent operations that are additional to the typical concrete supply chain.

Option	A.1	A.2	A.3	A.4	C.1	C.2	C.3	C.4
Cement (λ)	78.26	81.14	78.03	78.03	85.70	88.05	81.39	81.39
Nat. aggregates (μ)	4.54	1.84	1.84	1.84	4.58	1.84	1.85	1.85
Others (concrete) (ν)	5.06	3.62	3.61	3.79	5.57	4.03	4.01	4.41
CO₂ stored (θ)			-4.42	-5.77			-4.43	-5.63
Mineralization (α)			0.09	0.10			0.09	0.10
Evaporation (β)			0.01	0.01			0.01	0.01
Transport (γ)			0.01	0.01			0.01	0.01
Liquefaction (δ)			0.16	0.16			0.16	0.16
CO₂ supply (ρ)								
Aggregate recycling (λ)		1.78	1.77	1.77		1.78	1.78	1.78
Sum	87.9	88.4	81.1	79.9	95.8	95.7	84.9	84.1
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored			59.4	48.2			59.4	49.2
Difference relative to A.1 or C.1		1%	-8%	-9%		0%	-11%	-12%
GHG mitigation efficiency relative to A.1 or C.1 kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1 or C.1			37.4	34.0			23.4	23.0
Difference relative to A.2 or C.2			-8%	-10%			-11%	-12%
GHG mitigation efficiency relative to A.2 or C.2 kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.2 or C.2			34.8	31.9			23.7	23.3

b. Other environmental indicators

The analysis is completed by assessing the different supply chain scenarios concerning other (non-climate impact related) environmental indicators. We use the midpoint indicators provided by the Environmental Footprint method v.3.0. We decided to not use endpoint impact assessment methods providing a aggregated single scores such as provided by the Ecological Scarcity method developed by the Swiss Federal Office for Environment. While, different environmental impacts can also be aggregated to a single indicator representing “total environmental impacts” in regard to the Swiss policies such an



aggregation has been perceived by the research team as a subjective weighting of the different impacts. we consider thus such a single-score evaluation as out of scope of this report.

Table 11 shows that producing concrete with carbonated RCA via the capture and storage of biogenic CO₂ does not lead to increased impacts relative to using virgin aggregates or uncarbonated RCA among the indicators included in the Environmental Footprint method v.3.0, except for the following indicators (Figure 24): Ozone Depletion Potential, Ionizing Radiation Potential and Human Toxicity, carcinogenic. For Ozone Depletion Potential and Human Toxicity, carcinogenic, the impact increase is only observed relative to producing concrete with uncarbonated RCA. The increased electricity use is the main driver for the relative increase for these three indicators, as also indicated in Figure 24. This is especially true for Ionizing Radiation Potential, which stems from the use of nuclear power (i.e., mainly the disposal of uranium mining waste), but also for Ozone Depletion Potential, which is rooted in the use of ozone-depleting gases in compressors to transport certain fuels, such as natural gas. Apart from reducing its electricity use, it seems difficult for neustark or similar stakeholders to mitigate such impacts as it lies outside its direct zone of influence, besides establishing a power purchase agreement targeting specific energy sources.

However, a second driver for Ozone Depletion Potential is the production and leakage of refrigerant (R134a) at the Liquefaction stage and the use of stainless-steel infrastructure at the Mineralization stage for the indicator of Human Toxicity, carcinogenic. Using an “ozone-friendly” substitute for the liquefaction plant compressor, such as R-600a or R-290, could limit the increase in Ozone Depletion Potential from +11% to +7% with respect to using uncarbonated RCA. The remaining +7% can only be mitigated via reduced electricity use, which seems difficult, or via a renewables-based power purchase agreement. Similarly, extending the lifetime of the mineralization plant from 5 to 10 years would reduce the impacts for Human Toxicity, carcinogenic from +9% to +1%, with respect to using uncarbonated RCA.

Table 11 Changes in impacts caused by using carbonated RCA (A.3, A.4, C.3, C.4) to produce a ton of concrete, relative to using virgin aggregates (A.1, C.1) or uncarbonated RCA (A.2, C.2), for the indicators of the life-cycle impact assessment method Environmental Footprint v.3.0.

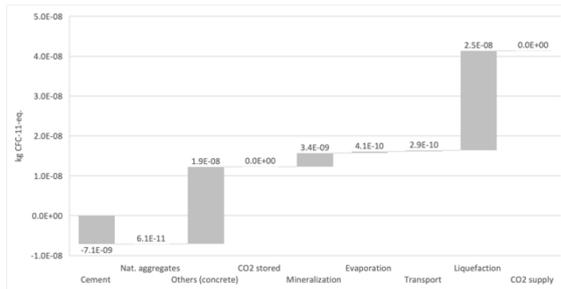
Option	A.1	A.2	A.3	A.4	C.1	C.2	C.3	C.4
	Ozone Depletion Potential							
Difference relative to A.1 or C.1		-9%	-4%	1%		-10%	-7%	2%
Difference relative to A.2 or C.2			6%	11%			3%	13%
	Acidification Potential							
Difference relative to A.1 or C.1		-3%	-6%	-6%		-4%	-10%	-9%
Difference relative to A.2 or C.2			-3%	-3%			-6%	-5%
	Freshwater Eutrophication							
Difference relative to A.1 or C.1		-3%	-6%	-5%		-4%	-9%	-9%



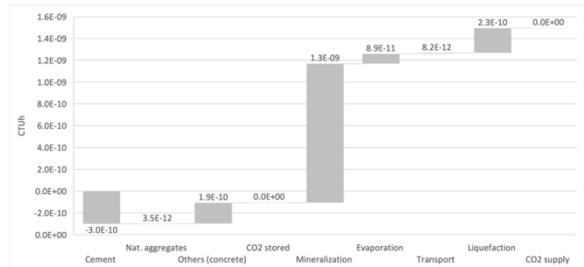
Option	A.1	A.2	A.3	A.4	C.1	C.2	C.3	C.4
Difference relative to A.2 or C.2			-3%	-2%			-6%	-5%
Marine Eutrophication								
Difference relative to A.1 or C.1		-4%	-6%	-6%		-4%	-10%	-9%
Difference relative to A.2 or C.2			-3%	-3%			-6%	-5%
Terrestrial Eutrophication								
Difference relative to A.1 or C.1		-4%	-7%	-6%		-4%	-10%	-10%
Difference relative to A.2 or C.2			-3%	-3%			-6%	-6%
Freshwater Ecotoxicity								
Difference relative to A.1 or C.1		-2%	-4%	-3%		-3%	-7%	-6%
Difference relative to A.2 or C.2			-2%	-1%			-5%	-4%
Respiratory Inorganics								
Difference relative to A.1 or C.1		-16%	-17%	-16%		-16%	-19%	-18%
Difference relative to A.2 or C.2			-1%	-1%			-4%	-2%
Photochemical Ozone Formation								
Difference relative to A.1 or C.1		-5%	-7%	-7%		-5%	-11%	-10%
Difference relative to A.2 or C.2			-3%	-2%			-6%	-5%
Ionizing Radiation Potential								
Difference relative to A.1 or C.1		-5%	24%	27%		-5%	21%	25%
Difference relative to A.2 or C.2			30%	34%			28%	32%
Human Toxicity - carcinogenic								
Difference relative to A.1 or C.1		-13%	-7%	-6%		-14%	-9%	-7%
Difference relative to A.2 or C.2			8%	9%			6%	8%
Human Toxicity - non-carcinogenic								
Difference relative to A.1 or C.1		-4%	-5%	-4%		-5%	-8%	-7%
Difference relative to A.2 or C.2			-1%	0%			-4%	-3%
Resource Use, Energy Carriers								
Difference relative to A.1 or C.1		-5%	-5%	-3%		-5%	-8%	-6%
Difference relative to A.2 or C.2			0%	1%			-3%	0%
Resource Use, Minerals and Metals								
Difference relative to A.1 or C.1		-3%	-3%	-2%		-4%	-6%	-4%
Difference relative to A.2 or C.2			0%	1%			-3%	-1%
Land Use								
Difference relative to A.1 or C.1		-22%	-22%	-21%		-22%	-23%	-22%
Difference relative to A.2 or C.2			0%	0%			-1%	0%
Water Use								



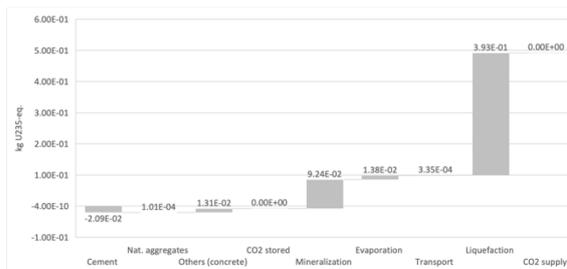
Option	A.1	A.2	A.3	A.4	C.1	C.2	C.3	C.4
Difference relative to A.1 or C.1		-16%	-16%	-15%		-15%	-18%	-17%
Difference relative to A.2 or C.2			-1%	0%			-3%	-2%



a) Ozone Depletion Potential



b) Human Toxicity, carcinogenic



c) Ionizing Radiation Potential

Figure 24 Increase in impacts caused by concrete production using carbonated RCA and carbonated slurry, relative to uncarbonated RCA. Interpretation of case a): A reduction in Ozone Depletion impacts is observed due to reduced cement use (-7.1×10^{-9}), but the subsequent steps amount to a positive impact contribution of about 4.7×10^{-8} , for a total impact of $\sim 4.0 \times 10^{-8}$ kg CFC-11-eq..

4. Discussion

The CO₂ mineralization supply chain, as operated by neustark, has a high energy and carbon removal efficiency, primarily due to 1) sourcing biogenic CO₂ and aggregate, which come without any embedded environmental burden (besides their conditioning and transport) and 2) having limited consumption of heat and electricity. Using carbonated RCA instead of (uncarbonated) RCA is also attractive, as it reduces cement use.

Our sensitivity analysis (see Appendix I) shows that the two instances capable of significantly hampering the CO₂ removal efficiency of the supply chain are 1) sourcing CO₂ from industrial emitters or Direct Air Capture (DAC), which require a substantial amount of heat and electricity, especially when combined with an electricity source that is more carbon intense than the current national Swiss average consumption mix (such as natural gas), and 2) allocating a share of the demolition waste recycling process to the RCA.

This sensitivity analysis also suggests that – based on current market values for biomethane and biogenic CO₂ – allocating environmental burden to the CO₂ from the biogas upgrading plant would not



significantly hamper the CO₂ removal efficiency of the supply chain (i.e., ~94% against 95% if the CO₂ is free of burden). This is a positive finding as biogenic CO₂ may be considered a commodity (similarly to the co-produced bioethane).

Finally, it is worth noting that while sourcing CO₂ from industrial emitters (i.e., from a cement plant, using MEA-based gas scrubbing) does not allow reaching comparable CO₂ removal efficiencies as in the Base scenario, they remain nonetheless good sourcing options (i.e., between 70% when sourced from DAC, to 75% when sourced from a cement or MSWI plant with captured CO₂ assumed to be biogenic) – although their economic and environmental (non-climate indicators) performance have not been quantified.

We have also shown that other aspects do not affect the CO₂ removal efficiency of the supply chain, such as the use or not of an electric reboiler and the carbon intensity of the electricity (provided the CO₂ is sourced free of burden). Other aspects not shown in this report have a limited effect, such as the type of vehicle powertrain used to transport the liquefied CO₂ (i.e., diesel, electric), the transport distance between the CO₂ supplier and the mineralization plant, and the CO₂ loss rate (within reasonable extent).

Additionally, we have shown that the risk of an increase in impacts for other environmental indicators is low. We identified Ozone Depletion Potential, Human Toxicity, carcinogenic, and Ionizing Radiation Potential as indicators that present increased impacts because of operating the liquefaction and mineralization plants compared to using uncarbonated RCA.

Finally, it seems a trade-off exists between the CO₂ removal efficiency of the supply chain (i.e., the amount of GHG emitted per ton of biogenic CO₂ removed from the atmosphere) and the overall amount of CO₂ stored in recycled aggregate yearly. This is because the CO₂ removal efficiency decreases with residence time. Although the mass of CO₂ stored per ton of RCA increases with the residence time, it does so marginally decreasingly while the energy expenditure increases linearly. In contrast, the yearly supply of recycled aggregate depends on how much demolition waste is treated and sorted that year. Hence, the operator will have to find an optimal trade-off between the carbon dioxide removal efficiency of the supply chain and the amount of CO₂ stored overall.

- **Task 5: End-of-demonstration evaluation of the overall value chain (month 22-24)**

The CO₂ supply chain and the CO₂ storage technologies have been operated for 15 months starting on the 01.05.2022 until the 31.07.2023. The year 2022 was used to reach stable operation of the plant by implementing learnings, while in 2023, a stable operation could be achieved with the RCA carbonation plant.

The aim of the project was to reach TRL 7 (system prototype demonstration in operational environment) to TRL 8 (system complete and quantified). TRL 7 was achieved in 2022, by operating the FOAK plant



with commercially available concrete aggregate and CO₂, while the continuous improvement of the technology on site of the Kästli plant increased its stability to a level such that it was deployed to carbonate all RCA of fraction 0/8 and 8/16 entering concrete mix designs – which consequently increased the TRL to 8.

Moreover, the concrete mixing water carbonation system was operated for a few months.

Throughout these operation, the RCA carbonation plant was storing 91 t of CO₂, while 4.4 t of CO₂ have been stored with the slurry carbonation plant.

Moreover, both technologies should be demonstrated at TRL 7/8. Since 1) the technologies represent full-scale FOAK plants, which can process the whole throughput of the industrial plant, 2) they have been integrated into the industrial processes and operated in the industrial environment with actual material streams for months, and 3) the system as such is complete and the critical assumptions could we qualified and quantified – the goal of demonstrating the technologies at TRL7/8 has been achieved.

However, the target of 500 t CO₂ sequestered has not been reached. This target value of 500 t CO₂ sequestered in 15 months of operation was derived from the typical volumes of recycled concrete aggregate Kästli Bau processes each year, assuming that 1) the plant will reach stable operations from day one and 2) the demand of RCA in concrete corresponds to a typical production year.

It turned out that these assumptions were too optimistic for the following reasons:

1. First-of-a-kind plant: Many lessons had to be learned, e.g., on the material handling and the process control. This led to significant downtimes – the plant ran only 50% of the time.
2. Reduced throughput due to lower demand for concrete on the market: 2022 and 2023 have been challenging for Swiss producers; deliveries have declined locally in a significant two-digit percent range. Since the plant is operated in line with the concrete production – the output of the concrete production determines the throughput of concrete aggregate.

In the following, the energy consumption, the net removal efficiency, and the costs of removal will be discussed:

1. Energy Consumption per t of CO₂-eq removed from the atmosphere

The system's energy consumption splits into the energy required to build the infrastructure (including the materials)³⁶ and the energy needed to operate the system. In operation, the liquefaction of CO₂ (277

³⁶ [Frontiers | Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector \(frontiersin.org\)](https://www.frontiersin.org/journal/10.3389/fenrg.2023.1158411)



kWh el./t CO₂), transport (11 MJ Diesel/t CO₂), and the storage plant (20 kWh el./t CO₂) consume energy. All these values have been measured. To obtain the exergy (which is the electrical equivalent work), we assume an primary energy to electricity conversion efficiency η of 40% and a removal efficiency of 94%.

$$\text{Primary Energy} = \frac{E_{\text{liqu}}}{\eta} + E_{\text{transport}} + \frac{E_{\text{storage}}}{\eta}$$

$$\text{Exergy} = E_{\text{liqu}} + \eta E_{\text{transport}} + E_{\text{storage}}$$

Thus, the primary energy of the overall value chain is 792 kWh/t CO₂ removed – or about 320 kWh/t CO₂ removed of exergy. This lies just above the originally targeted range of 150 – 300 kWh of exergy per t of CO₂-eq removed.

2. CO₂ removal efficiency

Two effects may reduce the efficiency of the value chain: 1) CO₂ molecules, which are not stored permanently but lost along the value chain, reflected in the CO₂ storage efficiency, and 2) emissions due to the consumption of energy and materials used to construct and operate the value chain. Both effects have been discussed in a previous publication. As mentioned above, out of 100 CO₂ molecules injected by the technology into the reaction chamber, 97.7 (RCA) and >99.5 (concrete mixing water) get stored permanently (= CO₂ storage efficiency). Moreover, PSI identified that in almost all relevant cases, the removal efficiency (amount of CO₂ removed over the amount of CO₂ stored) is >90%, while in the DemoUpCarma case, it is even 94%. Multiplying the CO₂ storage efficiency and the CO₂ removal efficiency gives a value of 92%. Therefore, we lie in the target range of >85%.

3. Cost

A simplified economic evaluation of the system has been made. The calculation considers the system's actual costs (CO₂ storage plant cost was about CHF 290'000), profit expectations on the capital (0%), and a payback period of the capital of 7 years. The energy was priced at 0.2 CHF/kWh, the transport at 50 CHF per ton of CO₂, the CAPEX for liquefying CO₂ was assumed to be about 40 CHF/t CO₂ removed, and we presume about 10'000 CHF in annual maintenance costs.

Thus – such systems have fixed costs from the plants (CAPEX), and variable costs (OPEX) from supplying CO₂ and maintaining the plants. The more CO₂ is sequestered, the smaller the fixed costs per ton of CO₂ – while the large chunk of the variable costs (CO₂ supply) remains unchanged.

In case the storage plant fixes 91 t of CO₂ over the course of the project (DemoUpCarma value) – the cost of each ton of CO₂ removed in this project was about 3600 CHF/t CO₂ removed. This assumes, that all costs are allocated to the project and the plant will not be used for further operations.



Since the plant has a further use – and is planned to operate at a nominal capacity of 500 t of CO₂ stored per year – the cost drops drastically to 261 per ton of CO₂ removed.

One has to consider that the main drivers for the cost are 1) the amount of CO₂ sequestered per year and 2) the profit expectations.

The challenges around the small amounts of CO₂ sequestered are already resolved in newer projects – thanks to the learnings made in this project. First, the technology learning led to an improved plant design and thus radically reduced downtime. Second, most plants today are placed directly in line with the crusher (breaking demolition concrete to aggregate), drastically increasing the RCA throughput.

High profits help rapid implementation of the technology – while it increases the cost. Moreover, this calculation does not include expenses related to monitoring, reporting, and certification of CO₂ credits and costs for coordinating the value chain. These MRV costs are composed of internal staff costs and external validation costs. If set up cost-efficiently (i.e., many plants are added to a program, avoiding annual fees on a per-project basis for projects <10'000 t CO₂), these costs remain account for about 5% of the overall costs of the value chain.



5 Conclusions

The results have been presented in many detail in the previous chapter. In the following, the highlights will be summarized and put in perspective.

In the project's scope, two industrial-scale, seamless, integrated technologies sequestering carbon dioxide in demolition concrete and concrete slurry waste have been designed, constructed, and commissioned at the Kästli concrete plant in Bern. In the continuous operation of the aggregate carbonation plant, about 91 t of CO₂, or 13 kg of CO₂ per ton of 0 to 16 mm concrete aggregate, have been sequestered, which corresponds to an increase of 60% benchmarked with the results of the RECARB project. Thus, the silo does not only outcompete the RECARB container system in terms of adequate storage capacity per ton of RCA – it also operates in line with the concrete production. It thus reduces the additional handling effort for the carbonation to a minimum since the RCA has to pass anyways through the silo before it is incorporated into concrete. This reduces costs and CO₂ emissions. On the other hand, the concrete slurry carbonation could fix about 25 kg of CO₂ per cubic meter of slurry (and 4.4 t CO₂ in total) – which transforms it into another key route to sequester large amounts of CO₂. Moreover, material tests have shown that carbonation decalcifies C-S-H and transforms it into a potentially reactive material that participates in the cement hydration reaction. Thus, carbonation effectively improves the characteristics of concrete aggregate and concrete slurry used for concrete. Finally, an Excel-based LCA framework has been developed, which allows the rapid modeling of various CCUS value chains and their comparison. It revealed that the scenarios with the highest industrial relevance currently show more than 90% efficiencies in removing carbon from the atmosphere (i.e., 95% for the Base scenario, using biogenic CO₂ from a biogas upgrading plant). The LCA work also shows that only a limited number of conditions can hamper such efficiency: sourcing CO₂ using energy-intensive means (such as direct air capture or MEA scrubbing at industrial point sources) and allocating some environmental burden to the supply of RCA. If none of these two conditions are realized, the supply chain's lifecycle-based CO₂ removal efficiency remains very good.

Moreover, the energy consumption (in exergy) of the entire value chain is 320 kWh/t of CO₂ removed. A simple cost calculation shows that costs in the target range of 250 – 350 CHF/t CO₂ removed are within reach if 1) the RCA throughput is increased significantly and 2) profit expectations do not change drastically.



6 Outlook and next steps

After the demonstration, the value chain will remain in commercial operation – removing CO₂ from the atmosphere. The project itself has had a notable impact on neustark's business. The plant commissioned and operated has been a world's first – and it helped generate credibility and traction. To date (31.12.2023), 12 commercial CO₂ storage plants are operating, and ten more are under construction. The technology rollout is ongoing in Switzerland, Germany, Austria and France. All plants together removed to date (31.12.2023) roughly 700 t of CO₂.

The technology in its current state (with regards to the technology readiness and the economics) will allow neustark to penetrate a significant fraction of the market – however, especially for small-scale recyclers – this solution is only suitable if CO₂ storage is a specification they have to meet to deliver their product on the market.

At this stage, the critical R&D questions on the technology and material sides have been answered. Now, it is very much about continuous improvement, which comes from operating the value chain and using learnings along the way.

Neustark's focus will remain on optimizing the plant designs and the process itself. The company's continuous improvement process aims to 1) store more CO₂ per ton of RCA and 2) drive down the cost of the technology – both will accelerate the widespread implementation.

Moreover – carbonation will help concrete producers and recyclers use concrete aggregate and slurry more optimally.

The future success of the solution depends on profit opportunities for the stakeholders involved in removing CO₂. Thus, reducing costs and developing a market for such solutions remains critical.

As a result of the DemoUpCarma Project and other activities in this space in Switzerland, The Climate Cent Foundation has selected 3 project developers in Switzerland to roll-out the CO₂ storage technology in the concrete production and concrete recycling sector until 2030.

Moreover, Entsorgung Recycling Zürich has opened a tender to transport and permanently store CO₂ emissions from their waste sludge incinerator in Zürich Werdhölzli.

The project itself has been concluded.



7 National and international cooperation

The technology has been exported to Austria, Liechtenstein, and Germany (where CO₂ storage plants are under construction). One storage plant operates in Berlin – Germany, demonstrating that this Swiss innovation managed to cross the border and can be exported and deployed in other countries.

F. Winnefeld (Empa) is a member of the technical commission TC-MCP (Accelerated mineral carbonation for the production of construction materials) of RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures). Within this committee, international experts from academia and industry exchange their experience in the fields of (1) carbonated construction aggregates, (2) carbonated materials as supplementary materials, (3) CO₂-hardened precast products including CO₂-cured conventional concrete, and (4) Test and evaluation methods for carbonated construction materials. See <https://www.rilem.net/groupe/mcp-accelerated-mineral-carbonation-for-the-production-of-construction-materials-442> for further details.

8 Publications

Leemann A., Winnefeld F., Münch B., Tiefenthaler J.: Accelerated carbonation of recycled concrete aggregates and its implications for the production of recycling concrete, *Journal of Building Engineering* 79 (2023), 107779.

Winnefeld F., Tiefenthaler J., Leemann A.: Carbonation of concrete slurry waste and its use as supplementary cementitious material, *International RILEM Conference on Synergising Expertise towards Sustainability and Robustness of Cement-based Materials and Concrete Structures (Synercrete '23)*, June 15-16, 2023, Milos Island, Greece, 562-571.

Winnefeld F., Tiefenthaler J., Leemann A.: Influence of carbonated calcium silicates on cement hydration, *12th ACI/RILEM International Conference on Cementitious Materials and Alternative Binders for Sustainable Concrete (ICCM2024)*, June 23-26, Toulouse, France, submitted.

Winnefeld F., Tiefenthaler J., Leemann A.: Use of carbonated recycled aggregate and concrete slurry waste in recycling concrete – results of the Swiss “DemoUpCarma”-project, *1st RILEM International Conference on Mineral Carbonation for Cement and Concrete*, April 16-17, Aachen, Germany, abstract submitted.

Winnefeld F., Tiefenthaler J., Leemann A.: Carbonated concrete slurry waste as supplementary cementitious material, *Journal of Advanced Concrete Technology (Special Issue Synercrete '23)*, in preparation.



Appendix I

Sensitivity analyses on life-cycle assessment results

A series of sensitivity analyses are conducted on the different components of the mineralization supply chain to test the robustness of the results presented in the core section of the report. Hence, we use contrasting assumptions regarding the supply of RCA, CO₂, electricity source, etc., and quantify the deviation in results compared to the Base scenario presented in Section 4.

Source and transport of CO₂

Table 12 presents variants of the Base scenario with different CO₂ sourcing options for mix design A, with respect to Option A.1 (i.e., virgin aggregate) and Option A.4 (using carbonated RCA, with CO₂ sourced from WWTP, free of environmental burden). Should the biogenic CO₂ from the biogas plant receive a share of the environmental burden from the upgrading process based on its market value, this would not significantly affect the supply chain carbon removal efficiency (based on the market values considered). This contrasts with sourcing biogenic CO₂ from industrial emitters or via Direct Air Capture. It is, however, essential to recognize that industrial sources of biogenic CO₂ are constrained in supply (i.e., the supply will not increase to accommodate an increasing demand) despite a current untapped potential.

Table 12 Global Warming Impacts over a 100-year time horizon, in kilograms of CO₂-eq. for one-ton concrete following the concrete mix design A, using different biogenic CO₂ sources. DAC = Liquid solvent-based Direct Air Capture. MSWI = Municipal Solid Waste Incineration plant.

Option	A.1	A.4 (CO ₂ "free-of-burden")	A.4 (allocated biogenic CO ₂ from biogas upgrading)	A.4 (biogenic CO ₂ from cement plant)	A.4 (biogenic CO ₂ from MSWI plant)	A.4 (CO ₂ from DAC)
Cement	78.26	78.03	78.03	78.03	78.03	78.03
Nat. aggregates	4.54	1.84	1.84	1.84	1.84	1.84
Others (concrete)	5.06	3.79	3.79	3.79	3.79	3.79
CO₂ stored		-5.77	-5.77	-5.77	-5.77	-5.77
Mineralization		0.10	0.10	0.10	0.10	0.10
Evaporation		0.01	0.01	0.01	0.01	0.01
Transport		0.01	0.01	0.01	0.01	0.01
Liquefaction		0.16	0.16	0.16	0.16	0.16
CO₂ supply			0.06	1.12	1.17	1.42
Aggregate recycling		1.77	1.77	1.77	1.77	1.77
Sum	87.9	79.9	80.01	81.06	81.12	81.37
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored		48.2	58.9	241.7	251.0	295.0



Difference relative to A.1		-9%	-9%	-8%	-8%	-7%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1		34.0	41.5	170.3	176.8	207.8

Residence time

The residence time values considered for this sensitivity analysis are presented in Table 13. The values for stored CO₂ per ton of aggregate are valid for a specific size distribution, specified in Section 4.2.c. Figure 25 confirms that the amount of CO₂ stored correlates positively with the residence time. However, it also shows that, between a residence time of 5 hours and 48 hours, the amount of CO₂ stored increases by ~36%, while the GHG emissions related to mineralization grow by 82%. This is because of the non-linear nature of the CO₂ mineralization process, which slows down over time, while energy-related expenditures do not. Table 14 shows that the highest CO₂ removal efficiency (the lowest amount of GHG emissions emitted per ton of CO₂ stored) is reached for a residence time between 1 and 3 hours. Considering GHG emissions mitigation (i.e., CO₂ removal and GHG emissions reduction), the numbers suggest keeping the residence time to a minimum. However, this is potentially incorrect as it assumes that a minimum carbonation level of the RCA would still ensure a reduction in cement use, which remains to be proven. Furthermore, keeping the residence time to a minimum reduces the overall amount of CO₂ stored in recycled aggregate – availability is constrained by the amount of demolition waste to treat. Hence, a trade-off exists between the CO₂ removal efficiency of the supply chain and the overall amount of CO₂ to store. This trade-off would eventually be decided by economics and the choices made by the operator to maximize profitability.

Table 13 Residence time and corresponding CO₂ storage in recycled concrete aggregate. These numbers exclude the cement sourcing and concrete mixing steps. Source for the first two columns: neustark

Residence time [hours]	kg CO ₂ stored/ton aggregate	Amount of greenhouse gas emitted per kg of CO ₂ stored
0.5	7.3	83.9
1	9.5	77.2
1.5	10.8	74.3
2	11.7	72.8
3	12.3	72.1
5	13.7	70.8
8	15.2	70.1
24	18.7	72.8
48	20.2	81.3

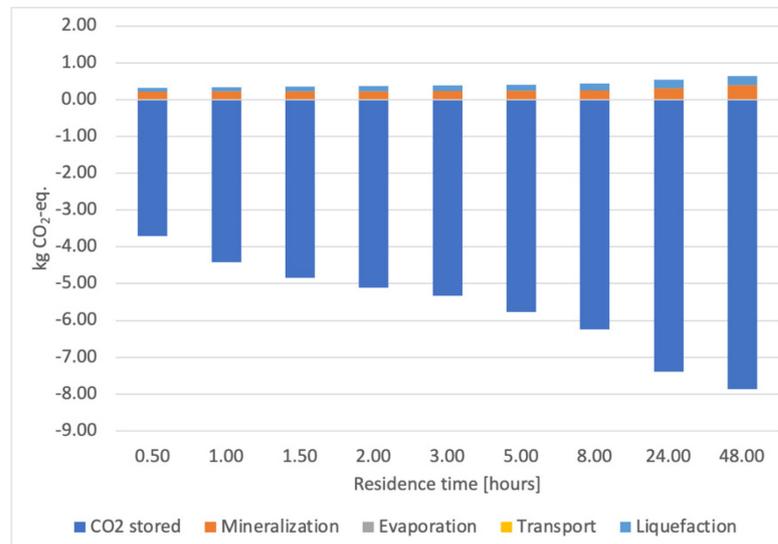


Figure 25 Change in greenhouse gas emissions (CO₂ stored in RCA and GES emitted) as a function of RCA residence time in the mineralization silo (in hours). Contributions that do not change are removed (e.g., cement, etc.).

Table 14 Greenhouse gas emissions per ton of concrete produced, with virgin (uncarbonated) and carbonated recycled aggregate, with different residence times in the CO₂ silo.

Concrete mix design/residence time	A.1	A.2	A.4 (0.5h)	A.4 (1h)	A.4 (1.5h)	A.4 (2h)	A.4 (3h)	A.4 (5h)	A.4 (8h)	A.4 (24h)	A.4 (48h)
kg CO ₂ stored per ton carbonated recycle aggregate			7.3	9.5	10.8	11.7	12.3	13.7	15.2	18.7	20.2
Cement	78.26	81.14	78.03	78.03	78.03	78.03	78.03	78.03	78.03	78.03	78.03
Nat. aggregates	4.54	1.84	1.84	1.84	1.84	1.84	1.84	1.84	1.84	1.84	1.84
Others (concrete)	5.06	3.62	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79
CO ₂ stored			-3.71	-4.42	-4.84	-5.12	-5.32	-5.77	-6.25	-7.40	-7.87
Mineralization			0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.17	0.25
Evaporation			0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Transport			0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Liquefaction			0.09	0.11	0.13	0.14	0.14	0.16	0.18	0.22	0.24
CO ₂ supply											
Aggregate recycling		1.78	1.78	1.78	1.78	1.78	1.77	1.77	1.77	1.77	1.76
Sum	87.9	88.4	81.9	81.2	80.8	80.6	80.4	79.9	79.5	78.4	78.1
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored			48.7	47.6	47.3	47.2	47.6	48.2	49.2	55.2	64.8
Difference relative to A.1 or C.1			-6.8%	-7.5%	-8.0%	-8.3%	-8.5%	-9.0%	-9.5%	-10.7%	-11.1%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1 or C.1			29.5	30.8	31.5	32.1	32.7	33.9	35.4	41.5	49.5
Difference relative to A.2 or C.2			-7.3%	-8.1%	-8.5%	-8.8%	-9.1%	-9.5%	-10.1%	-11.2%	-11.7%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.2 or C.2			27.2	28.6	29.4	30.0	30.6	31.9	33.4	39.4	47.1



Source of electricity

The amount of GHG emitted per ton of concrete produced with carbonated RCA, relative to using virgin or (uncarbonated) RCA, using different electricity technologies, is presented in Table 15. Results show that the electricity's type and carbon intensity level have some effect on the results. Still, in the worst case (i.e., where electricity is produced from natural gas), the CO₂ removal efficiency of the value chain is still close to 90% (i.e., ~100 kg CO₂-eq. per ton of biogenic CO₂ removed from the atmosphere). This is because the supply chain considered for our Base scenario, where CO₂ and aggregates are sourced free of burden – besides conditioning and transport – has a relatively low electricity requirement. The weight of electricity is significantly higher when the CO₂ is sourced from alternative suppliers (e.g., when sourced from Direct Air Capture, Table 16). In such a case, a CO₂ removal efficiency of 85% seems unreachable unless nuclear or hydropower is used.

Table 15 Greenhouse gas emissions per ton of concrete produced, with different electricity mix and technologies, with free-of-burden CO₂ from a biogas upgrading plant.

	A.1	A.2	A.4 (national mix)	A.4 (solar PV)	A.4 (Natural gas)	A.4 (Hydropower)	A.4 (Nuclear)
Cement	78.26	81.14	78.03	78.03	78.03	78.03	78.03
Nat. aggregates	4.54	1.84	1.84	1.84	1.84	1.84	1.84
Others (concrete)	5.06	3.62	3.79	3.62	4.28	3.54	3.54
CO ₂ stored			-5.77	-5.77	-5.77	-5.77	-5.77
Mineralization			0.10	0.08	0.16	0.07	0.07
Evaporation			0.01	0.01	0.02	0.00	0.00
Transport			0.01	0.01	0.01	0.01	0.01
Liquefaction			0.16	0.07	0.43	0.02	0.02
CO ₂ supply							
Aggregate recycling		1.78	1.78	1.77	1.77	1.77	1.77
Sum	87.9	88.4	81.9	79.66	80.77	79.52	79.52
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored			48.2	28.1	106.0	17.8	17.9
Difference relative to A.1 or C.1		0.6%	-6.8%	-9.3%	-8.1%	-9.5%	-9.5%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1 or C.1			34.0	19.4	79.4	12.1	12.2
Difference relative to A.2 or C.2			-7.3%	-9.9%	-8.6%	-10.0%	-10.0%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.2 or C.2			32.0	18.3	74.3	11.4	11.5



Table 16 Greenhouse gas emissions per ton of concrete produced, with different electricity mix and technologies, sourcing CO₂ from a Direct Air Capture plant.

	A.1	A.2	A.4 (national mix)	A.4 (solar PV)	A.4 (Natural Gas)	A.4 (Hydropower)	A.4 (Nuclear)
Cement	78.26	81.14	78.03	78.03	78.03	78.03	78.03
Nat. aggregates	4.54	1.84	1.84	1.84	1.84	1.84	1.84
Others (concrete)	5.06	3.62	3.79	3.62	4.28	3.54	3.54
CO ₂ stored			-5.77	-5.77	-5.77	-5.77	-5.77
Mineralization			0.10	0.08	0.16	0.07	0.07
Evaporation			0.01	0.01	0.02	0.00	0.00
Transport			0.01	0.01	0.01	0.01	0.01
Liquefaction			0.16	0.07	0.43	0.02	0.02
CO ₂ supply			1.42	0.93	2.85	0.67	0.68
Aggregate recycling		1.78	1.77	1.77	1.77	1.77	1.77
Sum	87.9	88.4	81.37	80.59	83.62	80.19	80.19
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored			295.0	189.0	600.5	134.5	135.0
Difference relative to A.1 or C.1		0.6%	-7.4%	-8.3%	-4.8%	-8.7%	-8.7%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1 or C.1			207.8	130.4	449.7	91.9	92.2
Difference relative to A.2 or C.2			-7.9%	-8.8%	-5.4%	-9.3%	-9.3%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.2 or C.2			195.4	122.8	421.2	86.5	86.8

Allocation of recycled aggregate

Here, we test the allocation key to split the environmental burden related to sorting demolition waste and producing RCA. In the Baseline scenario, the RCA is supplied free of burden besides its transport to the mineralization plant. Namely, we test the effect of a market value-based and mass-based allocation key on the supply chain's biogenic CO₂ removal efficiency and GHG emissions mitigation efficiency. Results are shown in Table 17. The allocation key chosen to allocate the burden of processing demolition waste does not affect the biogenic CO₂ removal efficiency of the value chain. This is simply because GHG emissions related to the RCA supply are not considered in the formula used to calculate this indicator.



However, using a market value or mass-based allocation key for the sourcing of RCA would imply more GHG emissions per ton of concrete produced relative to using virgin aggregate (i.e., A.4 (RCA burden based on economic allocation) vs. A.1). Hence, if the RCA does not come free-of-burden, its use to mineralize cement and store biogenic CO₂ can be questioned if the alternative is to produce concrete with virgin aggregate.

Table 17 Greenhouse gas emissions per ton of concrete produced, with virgin aggregate (A.1), free-of-burden carbonated recycled aggregate (A.4) and carbonated recycled aggregate with mass and economic allocation.

	A.1	A.2 (RCA, uncarbonated)	A.4 (RCA free-of-burden)	A.4 (RCA burden based on economic allocation)	A.4 (RCA burden based on mass allocation)
Cement	78.26	81.14	78.03	78.03	78.03
Nat. aggregates	4.54	1.84	1.84	1.84	1.84
Others (concrete)	5.06	3.62	3.79	3.79	3.79
CO ₂ stored	0.00	0.00	-5.77	-5.77	-5.77
Mineralization	0.00	0.00	0.10	0.10	0.10
Evaporation	0.00	0.00	0.01	0.01	0.01
Transport	0.00	0.00	0.01	0.01	0.01
Liquefaction	0.00	0.00	0.16	0.16	0.16
CO ₂ supply	0.00	0.00	0.00	0.00	0.00
Aggregate recycling	0.00	1.78	1.77	10.46	15.17
Sum	87.86	88.4	79.95	88.64	93.34
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored			48.2	48.2	48.2
Difference relative to A.1 or C.1		0.6%	-9%	1%	6%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1 or C.1			34.0	-554.4	-53.3

Reboiler

Table 18 presents the GHG emissions for producing one ton of concrete based on mix design A, where an electric boiler is used to different extents. Electrical reboilers are less energy-efficient than atmospheric ones. Naturally, as the use of electrical reboilers increases, the biogenic CO₂ removal efficiency decreases. However, that decrease is limited (i.e., 60 kg CO₂-eq./ton biogenic CO₂ removed from the atmosphere). Hence, using an electric reboiler, combined with an electricity source with a low carbon intensity, such as that of Switzerland, has a limited effect on the results.



Table 18 Greenhouse gas emissions per ton of concrete produced, with varying extent of electric boiler use, powered with the current national electricity consumption mix.

	A.1	A.2	A.4 (atm reboiler)	A.4 (5% electric reboiler)	A.4 (20% electric reboiler)	A.4 (35% electric reboiler)	A.4 (100% electric reboiler)
Cement	78.26	81.14	78.03	78.03	78.03	78.03	78.03
Nat. aggregates	4.54	1.84	1.84	1.84	1.84	1.84	1.84
Others (concrete)	5.06	3.62	3.79	3.79	3.79	3.79	3.79
CO ₂ stored	0.00	0.00	-5.77	-5.77	-5.77	-5.77	-5.77
Mineralization	0.00	0.00	0.10	0.10	0.10	0.10	0.10
Evaporation	0.00	0.00	0.01	0.01	0.02	0.03	0.07
Transport	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Liquefaction	0.00	0.00	0.16	0.16	0.16	0.16	0.16
CO ₂ supply	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aggregate recycling	0.00	1.78	1.77	1.77	1.77	1.77	1.77
Sum	87.86	88.38	79.95	79.95	79.96	79.97	80.01
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored			48.2	48.7	50.4	51.6	59.5
Difference relative to A.1 or C.1		0.6%	-9.0%	-9.0%	-9.0%	-9.0%	-8.9%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1 or C.1			34.0	34.3	35.5	36.3	41.9
Difference relative to A.2 or C.2			-10%	-10%	-10%	-10%	-9%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.2 or C.2			31.9	32.3	33.4	34.1	39.4

Background prospective scenarios

Table 19 and Table 20 show the greenhouse gas emissions per ton of concrete product using virgin aggregates and carbonated RCA, respectively, for different years into the future, under two Swiss energy scenarios. Among the noteworthy trends, we can see that, regardless of the scenario, the efficiency of the supply chain, as represented in the Base scenario (i.e., free-of-burden CO₂ from biogas upgrading plant and free-of-burden recycled aggregate, aside from conditioning and transport), slightly improves over time, both in terms of biogenic CO₂ removal efficiency and GHG emissions mitigation efficiency. The improvement is purely caused by progressive decarbonization in the other sectors of the Swiss economy (e.g., production of cement, electricity, steel, etc.), reflected within the prospective background life-cycle database, not because of improvements along the mineralization value chain (which may occur in the future but are not considered here). The improvement is more pronounced in the ZERO Basis scenario.



Hence, by 2030, the biogenic CO₂ removal efficiency will increase by a factor of two, going from 50 kg CO₂-eq. per ton of CO₂ removed from the atmosphere to 22-27 kg. This is mainly due to a decrease in the carbon intensity level of the Swiss electricity mix, going from 135g CO₂-eq./kWh today to 56g CO₂-eq. and 42g CO₂-eq., according to the BAU and ZERO Basis scenarios, respectively. This has a direct effect on the contribution of the Liquefaction and Mineralization steps in terms of GHG emissions

Table 19 Greenhouse gas emissions per ton of concrete produced, using virgin aggregate and carbonated RCA, across two energy scenarios for Switzerland (BAU and ZERO Basis).

	Business-As-Usual						ZERO Basis					
	2030		2040		2050		2030		2040		2050	
	A.1	A.4	A.1	A.4	A.1	A.4	A.1	A.4	A.1	A.4	A.1	A.4
Cement	75.10	74.88	73.03	72.82	71.29	71.09	71.09	70.88	69.66	69.46	61.23	61.05
Nat. aggregates	3.82	1.55	3.28	1.33	2.80	1.13	3.19	1.29	2.74	1.11	1.39	0.56
Others (concrete)	4.61	3.38	4.27	3.13	3.75	2.80	4.38	3.18	4.03	2.90	3.68	2.73
CO ₂ stored		-5.77		-5.77		-5.77		-5.77		-5.77		-5.77
Mineralization		0.07		0.07		0.06		0.06		0.05		0.04
Evaporation		0.00		0.00		0.00		0.00		0.00		0.00
Transport		0.01		0.00		0.00		0.01		0.00		0.00
Liquefaction		0.07		0.07		0.05		0.06		0.03		0.03
CO ₂ supply		0.00		0.00		0.00		0.00		0.00		0.00
Aggregate recycling		1.70		1.56		1.31		1.63		1.53		1.32
Sum	83.53	75.89	80.58	73.22	77.84	70.68	78.65	71.35	76.43	69.31	66.30	59.97
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored		27.3		25.8		20.5		22.4		14.9		13.1
Difference relative to A.1		-9%		-12%		-15%		-15%		-17%		-28%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.1		20.2		19.8		16.3		17.4		11.9		11.8



Table 20 Greenhouse gas emissions per ton of concrete produced, using uncarbonated and carbonated RCA, across two energy scenarios for Switzerland (BAU and ZERO Basis).

	Business-As-Usual						ZERO Basis					
	2030		2040		2050		2030		2040		2050	
	A.2	A.4	A.2	A.4	A.2	A.4	A.2	A.4	A.2	A.4	A.2	A.4
Cement	77.86	74.88	75.72	72.82	73.92	71.09	73.71	70.88	72.23	69.46	63.48	61.05
Nat. aggregates	1.54	1.55	1.32	1.33	1.13	1.13	1.29	1.29	1.11	1.11	0.56	0.56
Others (concrete)	3.24	3.38	3.01	3.13	2.69	2.80	3.06	3.18	2.80	2.90	2.64	2.73
CO ₂ stored		-5.77		-5.77		-5.77		-5.77		-5.77		-5.77
Mineralization		0.07		0.07		0.06		0.06		0.05		0.04
Evaporation		0.00		0.00		0.00		0.00		0.00		0.00
Transport		0.01		0.00		0.00		0.01		0.00		0.00
Liquefaction		0.07		0.07		0.05		0.06		0.03		0.03
CO ₂ supply		0.00		0.00		0.00		0.00		0.00		0.00
Aggregate recycling	1.71	1.70	1.56	1.56	1.32	1.31	1.64	1.63	1.53	1.53	1.32	1.32
Sum	84.35	75.89	81.62	73.22	79.05	70.68	79.70	71.35	77.67	69.31	68.01	59.97
CO₂ removal efficiency kg CO ₂ -eq. emitted per ton CO ₂ stored		27.3		25.8		20.5		22.4		14.9		13.1
Difference relative to A.2		-9%		-12%		-15%		-15%		-17%		-28%
GHG mitigation efficiency kg CO ₂ -eq. emitted per ton CO ₂ -eq. mitigated relative to A.2		18.2		17.4		13.9		15.3		10.2		9.3