METHODOLOGY

CARBON SEQUESTRATION THROUGH ACCELERATED CARBONATION OF CONCRETE AGGREGATE

SDG 13

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SUMMARY

This methodology is applicable for project activities aiming at sequestering CO_2 in demolished concrete (concrete aggregate). Through the applied processes of carbonation, concrete aggregate is exposed to an increased CO_2 concentration and the CO_2 reacts with the cement phase of the concrete aggregate which contains calcium oxides to form stable carbonate minerals. Through the conversion to calcium carbonate ($CaCO_3$), CO_2 is permanently stored. This is a natural process observed during the weathering of concrete structures. The methodology provides two different processes which use either direct or the indirect mineral carbonation. Direct processes (a) imitate the natural process of weathering of concrete structures but increase the reaction rate through different factors such as an increased CO_2 concentration or an increased contact surface between the CO_2 and the cement phase. On the other hand, the indirect mineral carbonation process (b) extracts the cement phases by means of a solvent and carbonates it. As a result, calcium carbonate precipitates from the solvent. Both methods ((a) and (b)): 1) permanently store CO_2

as $CaCO_3$; 2) generate negative greenhouse gas emissions and 3) generate raw materials which are mostly used in the construction industry.

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1| Definitions

For the purpose of this methodology, the following definitions apply:

Calcination	Highly endothermic process where limestone is converted by thermal decomposition into calcium oxide and carbon dioxide.
Carbonation (Process)	CO_2 reacts with oxides such as calcium oxide or magnesium oxide to form stable carbonates. The carbonation reaction is exothermic. Carbonation of concrete happens when concrete is in contact with CO_2. The cement phase of the concrete is converted into $CaCO_3$.
Carbonation Plant	Plant, where concrete aggregate is being carbonated with a CO_2 rich gas stream at a specific temperature, pressure and optionally with a solvent, in either a direct or indirect manner in order to store CO_2.
Cement	Substance used for construction that hardens and adheres to other materials to bind them together. Cement is a mixture of ground clinker and additives such as gypsum, silica fume, slag, limestone and fly-ash.
Clinker	A homogeneous mixture of raw materials such as limestone, clay soil and iron ore are ground and heated in a kiln to a sintering temperature of approximately 1450°C to produce clinker. The clinker is then ground with additives into cement.
Concrete	Building material made from a mixture of gravel, sand, cement, and water.
Concrete Aggregate	Demolition concrete crushed and sieved to form concrete aggregate with a certain grain size distribution (usually comprising particle sizes from 0 to 32 mm)
Concrete Recycling Facility (CRF)	Facility, where demolished concrete is collected and processed into concrete aggregate. CRF do not produce concrete.
Demolition concrete	Includes all the waste produced by the construction and demolition of buildings and infrastructure made of concrete.
Gravel	Coarse primary aggregates with a grain size bigger than 4 mm and smaller than 32 mm.
Sand	Fine primary aggregates with a grain size smaller than 4 mm.
Carbonated Concrete Aggregate	Concrete aggregate that underwent the carbonation process and sequestered CO_2.

Regenerated Sand	Sand that results from the indirect mineral carbonation of concrete aggregate. In the first step of the process, calcium is extracted from the concrete aggregate using an acidic solution and the regenerated sand is filtered out.
Virgin Concrete	Concrete with a recycled material content below 25% by weight.

2| Scope, applicability and entry into force

2.1 | Scope

2.1.1 | This methodology is applicable to the activities that involves technology-based CO_2 sequestration through mineralization in recycled concrete aggregate[1] ,i.e., Carbonated Concrete Aggregate.

2.2 | Applicability

2.2.1 | This methodology is applicable for project activities that apply direct or indirect mineral carbonation (*Technologies 8.2 | below*) of demolished concrete.

2.2.2 | The proposed project activity uses concrete aggregate as a precursor to sequester CO_2 before it enters downstream processes - substitute gravel and sand or before it is landfilled. CO_2 sequestration can be achieved in the direct or indirect mineral carbonation process.

2.2.3 | This methodology is applicable under the following conditions:

a. Project may be implemented either at an existing or new facility producing concrete aggregate.

b. The source of CO_2 used shall be Direct Air Capture (DAC) or biogenic origin, i.e., CO_2 released as a result of the combustion or decomposition of organic material such as – organic fraction of municipal solid water (MSW), sludge or manure.[2] The project that involves use of non-biogenic sources of CO_2 may be considered for Gold Standard certification, however, the project developer shall seek prior approval with relevant revisions to this methodology as needed.

c. The project shall not result in any change in production capacity of the source of CO_2, process generating CO_2 and productive use of the biogenic CO_2 as compared pre-project situation.

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[1] The project developers may seek revisions to the methodology to include other potential mineral waste streams.

[2] The biogenic CO_2 is released from combustion or decomposition of organic waste and is subsequently captured to be stored in the concrete aggregate. Suitable sources amongst others are; waste treatment facilities such as animal waste, municipal waste, facilities using biomass for power and/or heat generation purposes.

d. Biomass treatment facilities that process biogenic wastes with non-biogenic wastes shall disclose the share of biogenic wastes that was treated at the end of the monitoring period.

e. In case, the biogenic CO_2 is sourced from processes that involves both fossil and biogenic CO_2 emissions, the amount of biogenic CO_2 emissions shall be determined according to the Monitoring and Reporting regulations of the European Emission Trading scheme (EUR-Lex - 02018R2066-20210101 - EN - EUR-Lex (europa.eu)) or equivalent. The amount of stored biogenic CO_2 shall not exceed the total biogenic CO_2 emissions of the respective CO_2 source within the same monitoring period.

f. If the source(s) of CO_2 used is part of any other carbon program or project, the project developer shall demonstrate in line with GS principles and requirements that no double-counting takes place.

g. If the carbonation plant is located within the same facility i.e., source of CO_2, the monitoring of the amount of total CO_2 production and consumption for carbonation shall be ensured.

h. The concrete with carbonated aggregate must fulfill the same quality standards as the concrete with non-carbonated aggregate while using the same amount of cement.

i. The $CaCO_3$ from the indirect mineral carbonation shall be used in applications and products where the $CaCO_3$ is neither thermally nor chemically decomposed. At the end of the monitoring period, project developer shall disclose and provide suitable evidence of the end use of the produced $CaCO_3$. In addition:

   i. The application of $CaCO_3$ as a filler material for the construction sector is considered as permanent storage of CO_2. For any other application of the $CaCO_3$, the storage of the CO_2 is considered by default non-permanent. Exceptions may be granted, if it can be proved that the CO_2 is permanently stored as $CaCO_3$ in the particular product/application and will not be released, i.e., through municipal solid waste incineration (MSWI) at the end of life of the product.

   ii. The $CaCO_3$ shall not be used in the clinker production, as this would release the CO_2 which was previously stored through carbonation.

2.3 | Safeguards

2.3.1 | The project shall not undermine or conflict with any national, sub-national or local regulations or guidance relevant to project activity.

2.3.2 | To avoid double counting or double claiming, the project developer shall clearly communicate to all project participants its ownership rights and intention of claiming emissions sequestered in the project activity. This must be communicated by contract or clear written assertions in the transaction paperwork. If the project developer is not the project technology end users, the end users shall be informed and notified that they cannot claim for emission reductions from the project.

2.3.3 | It is the project developer's responsibility to ensure that all data and monitoring requirements are met. Thus, the project developer shall make necessary arrangement that all needed data is available to the project developer. To this end, an agreement is needed between the project participants and the project developer.

2.4 | Entry into force

This methodology will enter into force the **7th March 2022**.

3| Normative references

This methodology also refers to the latest approved versions of the following CDM tools:

- TOOL 02 "Combined tool to identify the baseline scenario and demonstrate additionality"
- TOOL03 "Tool to calculate project or leakage CO_2 emissions from fossil fuel combustion";
- TOOL 07 "Tool to calculate the emission factor for an electricity system"
- TOOLl 11 "Assessment of the validity of the original/current baseline and to update of the baseline at the renewal of the crediting period";
- TOOL 12 "Project and leakage emissions from road transportation of freight"

4| Baseline methodology

4.1 | Project boundary

4.1.1 | The spatial extent of the project boundary includes the physical, geographical site of concrete recycling facility, carbonation plant, source of CO_2 and the site where the end products i.e., concrete aggregates and other are used at the end[3]

4.2 | Emissions sources included in the project boundary

4.2.1 | The project emissions include GHGs emissions associated with onsite power or energy consumption for the purpose of sourcing, processing and transportation of CO_2, operation of carbonation plant and/or transportation of concrete aggregate or regenerated sand from recycling facility, as applicable.

4.2.2 | For the indirect mineral carbonation process, the project boundary also includes the GHGs emissions associated with solvent supply.

[3] The end use of concrete aggregate shall be monitored on a qualitative basis through the parameter 'End use distribution' (CSAC 41), as prescribed in section 5.2 | below.

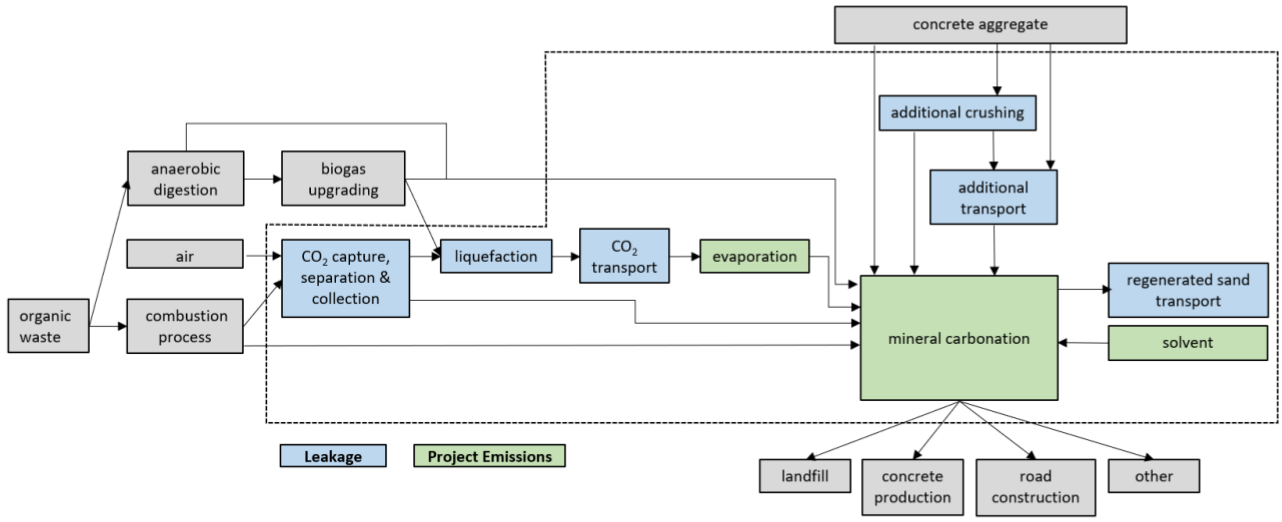

Figure 1 - Project boundary

4.2.3 | As long as the waste treatment or reuse of demolition concrete involves same steps in project and baseline scenario, associated emissions may be ignored and are not accounted for. If the demolition concrete involves additional processing steps to prepare it for carbonation purpose, for example crushing to smaller grain size distributions than in the baseline scenario to increase the uptake efficiency of the concrete aggregate, the GHGs emissions associated with energy consumption needed for this additional processing steps shall be accounted for, unless justified negligible.

4.2.4 | The products of the processes, namely carbonated concrete aggregate or recycled sand and $CaCO_3$ are afterwards used downstream for the production of new concrete and other products.

4.3 | Demonstration of additionality

4.3.1 | The additionality shall be demonstrated and assessed using the latest version of the "Combined tool to identify the baseline scenario and demonstrate additionality".

4.3.2 | The project developer shall provide transparent and documented evidence to demonstrate the additionality in line with applied additionality tool.

4.4 | Baseline scenario determination

4.4.1 | Project developer shall identify the most plausible baseline scenario among all realistic and credible alternatives(s). The latest approved version of the CDM Tool 02 "Combined tool to identify the baseline scenario and demonstrate additionality" shall be applied to assess which of these alternatives should be excluded from further consideration (e.g., alternatives where barriers are prohibitive or which are clearly economically unattractive). Where more than one credible and plausible alternative remains, project participants shall, as a conservative assumption, use the alternative baseline scenario that results in the lowest baseline emissions as the most likely baseline scenario.

4.4.2 | In doing so, project participants shall consider all realistic and credible scenarios for the treatment of demolition concrete and for the CO_2 originating from biogenic source, that are consistent with current rules and regulations in the host country or region, including the existing practice of demolition concrete treatment, the proposed project activity, and practices in other CRFs in the region using similar input raw materials, and facing similar economic, market and technical circumstances. The baseline alternatives shall be (but not limited to):

a. Landfilling of the demolished concrete without any prior treatment.
b. Crushing and sorting out the steel reinforcements bars and other useful materials from demolition concrete at sorting plants with further landfilling of concrete.
c. Crushing and sorting out the materials from demolition concrete with further recycling into new concrete (through its crushing into concrete aggregate and use in the preparation of new concrete or use in unbound form, e.g., construction of roads).
d. Landfilling of biogenic waste. Combustion of landfill gas without capture and storage of the CO_2 emissions.
e. Anaerobic digestion of biogenic waste, cleansing of the biogas through biogas upgrading and releasing of the separated CO_2 into the atmosphere.
f. Incineration of biogenic waste without capture and storage of the CO_2 emissions.
g. Anaerobic digestion of biogenic waste, cleansing of the biogas through biogas upgrading and storing of the separated biogenic CO_2 in concrete aggregate (proposed project activity which is realized without GS4GG certification consideration).
h. Combustion of landfill gas, capture and separation of the emitted CO_2 with subsequent storage in concrete aggregates (proposed project activity which is realized without GS4GG certification consideration).
i. Incineration of biogenic waste, capture and separation of the emitted CO_2 with subsequent storage in concrete aggregates (proposed project activity which is realized without GS4GG certification consideration).
j. Direct Air Capture with subsequent storage of the CO_2 in concrete aggregates (proposed project activity which is realized without GS4GG certification consideration).

4.4.3 | This Methodology is applicable only in case where it can be proven that alternative is: Demolition concrete is generated and used or landfilled and CO_2 originating from DAC or biogenic source is emitted to the atmosphere, where biogenic source is used to supply CO_2. *As a result, no carbonation plant is constructed and operated and no CO_2 is captured and supplied to the CO_2 carbonation plant,* is the most plausible baseline scenario.

4.5 | Baseline emissions

a. Ex-ante quantification of baseline emissions

4.5.1 | The baseline scenario does not generate any positive or negative emissions while the purpose of the project is to sequester biogenic CO_2 in concrete aggregate through mineral carbonation. By doing so, concrete aggregate serves as permanent sink. Therefore, the term “Project Sinks” is applied instead of the term “Baseline Emissions” in subsequent sections.

4.5.2 | Project Sinks are equivalent to the amount of CO_2 sequestered in carbonated concrete aggregate by applying direct or indirect mineral carbonation with biogenic CO_2 in the project activity. The ex-ante calculation is used to validate the amount of CO_2, measured ex-post, stored in one project sink.

4.5.3 | For the ex-ante calculation of Project Sinks, the following formula is applied:

$$\mathrm{GSC_y} = \sum_{i=1}^{n} \sum_{d=1}^{m} \mathrm{MG_{rep,i,d}} * \mathrm{SF}_{i,d} \quad \textit{Eq. 1}$$

Where:

$\mathrm{GSC_y}$	=	Gross Sink Capacity in the monitoring period y of the respective project sink (t CO_2)
$\mathrm{MG_{rep,i,d}}$	=	representative, cumulative mass of sub fractions *d* and material *i* (tconcrete aggregate) based on historical data or forecast. Material of type *i* can be distinguished in chemical composition. The amount of CO_2 stored depends on the grain size *d* of the material type *i*. To obtain a precise ex-ante estimation of the project sinks, the grain size distribution is split in *m* sub fractions of particles. The grain size distribution of material *i* may be experimentally determined (SN EN 12620) through, e.g., sieving. Alternatively, the data can also be sourced from data sheets from the crusher.
$\mathrm{SF}_{\mathrm{i},d}$	=	Sink factor corresponding to the specific amount of CO_2 that can be permanently fixed in the material *i* of grain size *d* (t CO_2/t concrete aggregate).

4.5.4 | The sink factor $\mathrm{SF}_{\mathrm{i},d}$ is a function of the grain size *d* and the quality of the material of type *i*. For this reason, the sink factor $\mathrm{SF_{i,d}}$ for each sub-fraction *d* of the material *i* has to be provided. Sink factors may be determined in lab scale measurements, based on previous measurements at industrial scale or they can be extracted from reports, data sheets or scientific literature. The following sink factors shall be used as default values for concrete aggregate with a low content (<5%) of other inert materials such as clay bricks[4]:

[4] Tiefenthaler et al. (2021).*In press*.

Grain size distribution	0-2 mm	2-4 mm	4-8 mm	8-16 mm	16-22 mm	>22 mm
SF_i	0.035	0.02	0.01	0.0075	0.006	0.005

b. Ex-post quantification of Baseline emissions

4.5.5 | Project Sinks are equivalent to the amount of CO_2 sequestered as $CaCO_3$ by carbonating concrete aggregate with CO_2 in the project activity.

4.5.6 | For ex-post quantification of project sinks, the following equations are applied. Gross Sink capacity (equivalent to the Project Sinks) is determined by the following formula:

$$PS_y = \sum_{i=1}^{n} \sum_{d=1}^{m} (m_{CO_2.i.d}^{in} - m_{CO_2,i,d}^{lost}) \quad \text{Eq. 2}$$

Where:

PS_y = The Project Sink (or Gross Sink Capacity) for the monitoring period y, (t CO_2) corresponds to the amount of CO_2 fed to the reactor system reduced by the amount of CO_2 leaving the reactor system as a gas.

$m_{CO_2,i,d}^{in}$ = Mass of CO_2 which was fed to the carbonation plant in the monitoring period y (t CO_2) to be stored in material i and grain size d.

$m_{CO_2,i,d}^{lost}$ = corresponds to the amount of CO_2 exiting the process without being stored in the monitoring period y (t CO_2). This value depends on the type of material i, the grain size d as well as on the technology deployed.

4.5.7 | The amount of CO_2 $m_{CO_2,i,d}^{lost}$ lost may be calculated as follows:

a. For Direct Mineral Carbonation:

1 m^3 reactor volume is filled with $\frac{\rho_{bulk,i,d}}{\rho_{i,d}}$ m^3 of material i and grain size d. $\rho_{bulk,i,d}$ and $\rho_{i,d}$ corresponds to the bulk density and the density of the material i, grain size d. The space in-between the concrete aggregate particles is filled with gas. The gas void fraction ϵ_i per m^3 of reactor volume can be calculated as follows:

$$\epsilon_{i,d} = 1 - \frac{\rho_{bulk,i,d}}{\rho_{i,d}} \quad \text{Eq. 3}$$

When 1 m^3 of the reactor volume is discharged, the material and $\epsilon_{i,d}$ m^3 gas of a CO_2 molar fraction $y_{i,d}^{CO_2}$ are discharged. In addition to that, if the plant has per design an exiting gas stream, the gas flow rate and composition is quantified with respective devices – to be able to quantify the amount of CO_2 $m_{CO_2,i,d}^{out}$ (t CO_2) exiting the process in the monitoring period y. Thus, the amount of CO_2 lost in the monitoring period y is:

$$\mathrm{m}^{\mathrm{lost}}_{\mathrm{CO_2,i,d}} = m^{out}_{CO_2,i,d} + \frac{\mathrm{p}*\mathrm{M_{CO_2}}}{R*T} * \epsilon_{\mathrm{i,d}} * \frac{\mathrm{y}^{\mathrm{CO_2}}_{\mathrm{i,d}}}{\rho_{\mathrm{bulk,i,d}}} * \mathrm{MG_{y,i,d}}$$ *Eq. 4*

M_{CO_2} is the molar mass of CO_2 in t per mole; p to the total pressure in Pascal, R to the ideal gas constant and T to the ambient temperature in Kelvin. $MG_{y,i,d}$ corresponds to the cumulative mass of sub fractions d and material i processed within the monitoring period y (tonnes concrete aggregate).

b. Indirect Mineral Carbonation:

The amount of CO_2 lost in a monitoring period is:

$$\mathrm{m}^{\mathrm{lost}}_{\mathrm{CO_2,i,d}} = \mathrm{m}^{\mathrm{out}}_{\mathrm{CO_2,i,d}}$$ *Eq. 5*

4.6 | Project emissions

4.6.1 | Project emissions are associated with activities related to the operation of carbonation plant for CO_2 treatment:

$$\mathrm{PE_y} = \mathrm{PE_{carbonation,y}} + \mathrm{PE_{evaporation,y}} + \mathrm{PE_{solvent,y}}$$ *Eq. 6*

Where:

PE_y	=	Project emissions in the monitoring period y, (t CO_2-eq.)
$PE_{carbonation,y}$	=	Project emissions due to operation of the carbonation plant in the monitoring period y, (t CO_2-eq.)
$PE_{evaporation,y}$	=	Emissions from consumption of energy, associated with the evaporation of CO_2 in the monitoring period y (t CO_2-eq.) If the carbonation plant is located at the CO_2 source and the CO_2 for the carbonation is directly sourced from the off-gas $PE_{evaporation,y} = 0$
$PE_{solvent,y}$	=	Emissions associated to the supply of solvent (t CO_2-eq.). Solvent is required only for the indirect mineral carbonation process. For the direct mineral carbonation process, the $PE_{solvent,y} = 0$.

4.6.2 | Project emissions due to the energy consumption of the carbonation plant are determined with the following formula:

$$\mathrm{PE_{carbonation,y}} = \mathrm{EC_{carbonation,y}} * \mathrm{EF_{el}} + \sum \mathrm{FC_{carbonation,i,y}} * \mathrm{NCV_i} * \mathrm{EF_{fuel,i}}$$ *Eq. 7*

Where:

$EC_{carbonation,y}$	=	Electricity Consumption of carbonation plant in monitoring period y (MWh)
EF_{el}	=	Emission factor of the consumed electricity (t CO_2-eq./MWh)

$FC_{carbonation,i,y}$	=	Consumption of fuel type i in year y used for operation of carbonation reactor (e.g. diesel generation for on-site electricity consumption) (t)
NCV_i	=	Net calorific value of fuel type i (MJ/t)
$EF_{fuel,i}$	=	Emission factor of fuel type i (tCO_2-eq./MJ)

4.6.3 | Emissions from consumption of energy, associated with the evaporation of CO_2 are determined by the following formula:

$$PE_{evaporation} = EC_{evaporation,y} * EF_{el} + \sum FC_{evaporation,i,y} * NCV_i * EF_{fuel,i}$$ *Eq. 8*

Where:

$EC_{evaporation,y}$	=	Electricity Consumption of CO_2 reboiler in monitoring period y (MWh)
EF_{el}	=	Emission factor of the consumed electricity (t CO_2-eq./MWh)
$FC_{evaporation,i,y}$	=	Consumption of fuel type i in year y used for operation of reboiler (e.g., diesel generation for on-site electricity consumption) (t)
NCV_i	=	Net calorific value of fuel type i (MJ/t)
$EF_{fuel,i}$	=	Emission factor of fuel type i (tCO_2-eq./MJ)

4.6.4 | Emissions associated to the production and supply of the solvent used for the indirect mineral carbonation process are determined by the following formula:

$$PE_{solvent,y} = SC_y * EF_{solvent}$$ *Eq. 9*

Where:

SC_y	=	Solvent Consumption of the indirect mineral carbonation process, ($t_{solvent}$)
$EF_{solvent}$	=	Emission factor of the solvent supply. A default value may be used for the $EF_{solvent}$ which considers the entire life cycle of the solvent for example refer to databases such as Ecoinvent. (t CO_2-eq./t solvent)

4.7 | Leakage

4.7.1 | Leakage emissions consist of:

a. Emissions due to the energy consumption associated with the additional crushing effort to reach higher CO_2 uptake efficiencies of the concrete aggregate
b. Emissions due to electricity and heat demand associated with the capture, separation and collection of the CO_2
c. Emissions due to the energy consumption of the CO_2 tank associated with refrigerating the CO_2

d. Emissions due to electricity consumption associated with the liquefaction of CO_2
e. Emissions associated with the transportation of liquefied CO_2 to the carbonation plant
f. Emissions associated with the transportation of concrete aggregate and regenerated sand

4.7.2 | The leakage emissions are calculated as follows:

$$LE_y = LE_{crusher,y} + LE_{capture,y} + LE_{liqu,y} + LE_{ref,CO_2,y} + LE_{tr,CO2,y} + LE_{tr,CA,y} + LE_{tr,CCA/sand,y} \quad \textit{Eq. 10}$$

Where:

LE_y	=	Leakage Emissions in monitoring period y, (t CO_2-eq.)
$LE_{crusher,y}$	=	Emissions due to energy consumption associated with the additional crushing effort in monitoring period y. If the demolition concrete is crushed to the same grain size distribution as in the baseline scenario: $LE_{crusher,y} = 0$
$LE_{capture,y}$	=	Emissions due to electricity and heat consumption associated with the separation, capture and collection of the CO_2 in monitoring period y. If the carbonation plant is located at the CO_2 source and the CO_2 for the carbonation is directly sourced from the off-gas: $LE_{capture,y} = 0$
$LE_{liqu,y}$	=	Emissions due to electricity consumption associated with the liquefaction of CO_2 in monitoring period y, (t CO_2-eq.) If the carbonation plant is located at the CO_2 source and the CO_2 for the carbonation is directly sourced from the off-gas: $LE_{liqu,y}=0$
$LE_{ref,CO_2,y}$	=	Emissions due to the refrigerating effort of the CO_2 tank. If a vacuum isolated tank is used without the requirement of refrigeration $LE_{ref,CO_2,y} = 0$
$LE_{tr,CO2,y}$	=	Emissions due to transportation of liquefied CO_2 from liquefying plant to the carbonation plant in monitoring period y, (t CO_2-eq.) If the carbonation plant is located at the CO_2 source and the CO_2 for the carbonation is directly sourced from the off-gas: $LE_{tr,CO2,y}=0$
$LE_{tr,CA,y}$	=	Emissions due to transportation of concrete aggregate from the CRF to the carbonation plant in monitoring period y, (t CO_2-eq.). These emissions only have to be considered when the carbonation plant is not located at the CRF.
$LE_{tr,CCA/sand,y}$	=	Emissions from transportation of carbonated concrete aggregate or regenerated sand from the carbonation plant to the location of treatment of the carbonated

concrete aggregate or regenerated sand in the monitoring period y, (t CO_2-eq.). These emissions only have to be considered when the carbonation plant is not located at the CRF

4.7.3 | Determination of Leakage due to the energy consumption associated with the additional crushing effort of the concrete aggregate

$$LE_{crusher,y} = EC_{crushing,y} * EF_{el} + \sum FC_{crusher,i,y} * NCV_i * EF_{fuel,i} \qquad \textit{Eq. 11}$$

Where:

$EC_{crusher,y}$	=	Electricity Consumption of the crusher for the additional crushing effort in monitoring period y (MWh)
EF_{el}	=	Emission factor of the consumed electricity (t CO_2-eq./MWh)
$FC_{crusher,i,y}$	=	Consumption of fuel type i in year y used for operation of the crusher for the additional crushing effort
NCV_i	=	Net calorific value of fuel type i (GJ/t)
$EF_{fuel,i}$	=	Emission factor of fuel type i (t CO_2-eq./GJ)

4.7.4 | Determination of Leakage due to the energy consumption for the capture, separation and collection of CO_2

$$LE_{capture,y} = EC_{capture,y} * EF_{el} + \sum FC_{capture,i,y} * NCV_i * EF_{fuel,i} \qquad \textit{Eq. 12}$$

Where:

$EC_{capture,y}$		Electricity consumption of the CO_2 capture, separation and collection process in monitoring period y (MWh)
EF_{el}	=	Emission factor of the consumed electricity (t CO_2-eq./MWh)
$FC_{capture,i,y}$	=	Consumption of fossil fuel(s) i for on-site power and heat generation for the capture, separation and collection process in monitoring period y.
NCV_i	=	Net calorific value of fuel type i (GJ/t)
$EF_{fuel,i}$	=	Emission factor of fuel type i (tCO_2-eq./GJ)

4.7.5 | Determination of Leakage due to energy consumption associated with the liquefaction of CO_2 are calculated by the following formula:

$$LE_{liqu,y} = EC_{liquefaction,y} * EF_{el} + \sum FC_{liquefaction,i,y} * NCV_i * EF_{fuel,i} \qquad \textit{Eq. 13}$$

Where:

$EC_{liquefaction,y}$	=	Electricity Consumption of liquefaction plant in monitoring period y (MWh)
EF_{el}	=	Emission factor of the consumed electricity (t CO_2-eq./MWh)
$FC_{liquefaction,i,y}$	=	Consumption of fuel type i in year y used for operation of the liquefaction plant (e.g. diesel generation for on site electricity consumption) (t)
NCV_i	=	Net calorific value of fuel type i (MJ/t)
$EF_{fuel,i}$	=	Emission factor of fuel type i (tCO_2-eq./MJ)

4.7.6 | Determination of leakage due to refrigerating effort of the CO_2 tank

$$LE_{ref,CO_2,y} = EC_{ref,CO_2,y} * EF_{el} + \sum FC_{ref,CO_2,i,y} * NCV_i * EF_{fuel,i}$$ *Eq. 14*

Where:

$EC_{ref,CO_2,y}$	=	Electricity Consumption of CO_2 tank in monitoring period y (MWh)
EF_{el}	=	Emission factor of the consumed electricity (t CO_2-eq./MWh)
$FC_{ref,CO_2,i,y}$	=	Consumption of fuel type i in year y used for the refrigerating effort of CO_2 tank
NCV_i	=	Net calorific value of fuel type i (MJ/t)
$EF_{fuel,i}$	=	Emission factor of fuel type i (t CO_2-eq./MJ)

4.7.7 | Determination of leakage due to transportation of liquefied CO_2, concrete aggregate and regenerated sand:

Emissions from transportation of liquefied CO_2, concrete aggregate or regenerated sand shall be determined using the CDM tool 12 "Project and Leakage Emissions from Transportation of Freight". Option A: Monitoring fuel consumption is recommended, however, alternatively, Option B: Using conservative default values of Tool 12 may be applied as follows:

$$LE_{tr,CO2,y} = \sum D_{CO2,f,y} * FR_{CO2,f,y} * EF_{tr,f}$$ *Eq. 15*

Where:

$LE_{tr,CO2,y}$	=	Emissions due to transportation of liquefied CO_2 from the CO_2 source to the carbonation plant in the monitoring period y, (t CO_2-eq.)
$D_{CO2,f,y}$	=	Round trip distance between the CO_2 source and the carbonation plant of freight transportation activity f in monitoring period y (km)

$FR_{CO2,f,y}$	=	Total mass of freight transported in freight transportation activity f in monitoring period y (tons)
$EF_{tr,f}$	=	Default CO_2 emission factor for freight transportation activity f (t CO_2-eq./t km).
f	=	Freight transportation activities conducted in the project activity in monitored period y

Emissions from transportation of concrete aggregate from the CRF to the carbonation plant:

$$LE_{tr,CA,y} = \sum D_{CA,e,y} * FR_{CA,e,y} * EF_{Tr,e} \quad \textit{Eq. 16}$$

Where:

$LE_{tr,CA,y}$	=	Emissions from transportation of concrete aggregate from the CRF to the carbonation plant in the monitoring period y, (t CO_2-eq.)
$D_{CA,e,y}$	=	Round trip distance between CRF and carbonation plant of freight transportation activity e in monitoring period y (km)
$FR_{CA,e,y}$	=	Total mass of freight transported in freight transportation activity e in monitoring period y (tons)
$EF_{tr,e}$	=	Default CO_2 emission factor for freight transportation activity e (t CO_2-eq./t km).
e	=	Freight transportation activities conducted in the project activity in monitored period y

Emissions from transportation of carbonated concrete aggregate or regenerated sand from the carbonation plant to the location of downstream use (e.g. concrete producer). These emissions are only to be accounted for if the carbonated concrete aggregate or the regenerated sand do not go back to the CRF. If they are returned to the CRF, the calculated emissions by applying equation 16 can be multiplied by a factor of two to account for the transport's emissions of the carbonated concrete aggregate or regenerated sand.

$$LE_{tr,CCA/sand,y} = \sum (D_{CCA/sand,g,y} - D_{sand,baseline}) * FR_{CCA/sand,g,y} * EF_{Tr,g} \quad \textit{Eq. 17}$$

Where:

$LE_{tr,CCA/sand,y}$	=	Emissions from transportation of carbonated concrete aggregate or regenerated sand from the carbonation plant to the location of downstream use in the monitoring period y, (t CO_2-eq.)
$D_{CCA/sand,g,y}$	=	Round trip distance between carbonation plant and location of downstream use of carbonated concrete aggregate or regenerated sand of freight transportation activity g in monitoring period y (km)

$D_{sand,baseline}$	=	Average round trip distance between CRF and downstream use of concrete aggregate (e.g. concrete production facility) in baseline scenario.
$FR_{CCA/sand,g,y}$	=	Total mass of freight transported in freight transportation activity g in monitoring period y (tons)
$EF_{tr,g}$	=	Default CO_2 emission factor for freight transportation activity g (t CO_2-eq./t km).
g		Freight transportation activities conducted in the project activity in monitored period y

4.7.8 | Project emissions related to leakage of CO_2 from the carbonation reactor during the carbonation process. A certain amount of CO_2 is lost during the carbonation process and escapes through the exit stream to the atmosphere. The methodology is only applicable for DAC or CO_2 originating from biogenic sources; therefore CO_2 leakage is considered as neutral and are not accounted in the calculation of the total Project Emissions/leakage emissions.

4.8 | Emission reductions

4.8.1 | The emission reductions are calculated as follows:

$$ER_y = PS_y - PE_y - LE_y$$ *Eq. 188*

Where:

ER_y	=	t CO_2-eq. removed in the monitoring period *y* due to project activity
PS_y	=	Project sinks in the monitoring period *y* (t CO_2-eq.)
PE_y	=	Project emissions in the monitoring period *y* (t CO_2-eq.)
LE_y	=	Leakage emissions in the monitoring period *y* (t CO_2-eq.)

5| Monitoring methodology

5.1 | Data and parameters not monitored

5.1.1 | In addition to the data and parameters listed below, the guidance on all tools to which this methodology refers applies. Thus, it is recommended also to refer to specific guidelines and tools applied in methodology, as not all parameters may be listed in this section.

Parameter ID	**CSAC 1**
Data / Parameter:	$MG_{rep,i,d}$
Data unit:	t (ton)
Description:	Representative, cumulative mass of sub fractions d and material i before treatment (t concrete aggregate)
Measurement procedures (if any):	-
Source of data:	Based on historical production of concrete aggregate or forecast
Any comment:	-

<table>
<tr><th>Parameter ID</th><th>CSAC 2</th></tr>
<tr><td>Data / Parameter:</td><td>$SF_{i,d}$</td></tr>
<tr><td>Data unit:</td><td>t CO_2-eq./t material</td></tr>
<tr><td>Description:</td><td>Sink factor as a function of the type of material i and grain size distribution d – defines approx. amount of CO_2 that can be sequestered by material of type i per unit mass of input material</td></tr>
<tr><td>Measurement procedures (if any):</td><td>-</td></tr>
<tr><td>Source of data:</td><td>Determined in experiments, based on previous industrial tests or sourced from reports or scientific literature. Default values for concrete aggregate (>95 purity), are listed in the table below:
<table>
<tr><td>Grain size distribution</td><td>0-2 mm</td><td>2-4 mm</td><td>4-8 mm</td><td>8-16 mm</td><td>16-22 mm</td><td>>22 mm</td></tr>
<tr><td>SF_i</td><td>0.035</td><td>0.02</td><td>0.01</td><td>0.0075</td><td>0.006</td><td>0.005</td></tr>
</table></td></tr>
<tr><td>Any comment:</td><td>-</td></tr>
</table>

Parameter ID	**CSAC 3**
Data / Parameter:	P
Data unit:	Pascal
Description:	Average local ambient pressure

Source of data:	-
Measurement procedures (if any):	Averaged annual pressure measured close by at e.g., a weather station. Default:101,325 Pa (standard pressure)
Any comment:	–

Parameter ID	CSAC 4
Data / Parameter:	T
Data unit:	Kelvin
Description:	Average annual ambient temperature of the project location
Source of data:	Publicly available sources, i.e., weather station report from area close by.
Measurement procedures (if any):	-
Any comment:	–

Parameter ID	CSAC 5
Data / Parameter:	M_{CO2}
Data unit	t/mol
Description:	Default Molar Mass of CO_2
Source of data:	0.000044 kg/mol
Measurement procedures (if any):	-
Any comment:	-

Parameter ID	CSAC 6
Data / Parameter:	$\rho_{bulk,i,d}$
Data unit:	kg/m^3
Description:	Bulk density of material of type i
Source of data:	On-site measurements
Measurement procedures (if any):	Options to determine $\rho_{bulk,i,d}$ (in order of preference): 1) Measured once according to the norm SN EN 1097-3 (or equivalent) 2) Reports, data sheets or scientific literature 3) Default value: 1500 kg/m^3
Any comment:	Measured once at the beginning of the project

Parameter ID	CSAC 7
Data / Parameter:	$\rho_{i,d}$
Data unit:	kg/m^3

Description:	Density of material of type i
Source of data:	On-site measurements
Measurement procedures (if any):	Options to determine $\rho_{i,d}$ (in order of preference): 1) Measured once according to the norm SN EN 1097-6 (or equivalent) 2) Reports, data sheets or scientific literature 3) Default value: 2400 kg/m^3
Any comment:	Measured once at the beginning of the project

Parameter ID	**CSAC 8**
Data / Parameter:	$EF_{tr,f}$
Data unit:	t CO_2-eq./t km
Description:	Default CO_2 emission factor for freight transportation activity f
Source of data:	Latest version of CDM tool 12 "Project and Leakage Emissions from Transportation of Freight" The emission factor can also be sourced from other third party published databases (e.g. Ecoinvent)
Measurement procedures (if any):	-
Any comment:	-

Parameter ID	**CSAC 9**
Data / Parameter:	$EF_{tr,e}$
Data unit:	t CO_2-eq./t km
Description:	Default CO_2 emission factor for freight transportation activity e
Source of data:	Latest version of CDM tool 12 "Project and Leakage Emissions from Transportation of Freight" The emission factor can also be sourced from third party published databases (e.g. Ecoinvent)
Measurement procedures (if any):	-
Any comment:	-

Parameter ID	**CSAC 10**
Data / Parameter:	$EF_{tr,g}$
Data unit:	t CO_2-eq./t km
Description:	Default CO_2 emission factor for freight transportation activity g

Source of data:	Latest version of CDM tool 12 "Project and Leakage Emissions from Transportation of Freight". The emission factor may also be sourced from third party published databases (e.g. Ecoinvent)
Measurement procedures (if any):	-
Any comment:	-

Parameter ID	**CSAC 11**
Data / Parameter:	EF_{el}
Data unit:	t CO_2-eq./MWh
Description:	Emission factor of national/regional power grid in the host country.
Source of data:	**For projects/activities located in Annex 1 countries**, any one of the following sources shall be used: a. Official grid emission factors published by host country governments b. Grid emission factors published as CDM standardized baseline approved by the CDM Executive Board. **For projects/activities located in non-Annex 1 countries**, any one of the following sources shall be used: a. Applying latest version of CDM TOOL 07 "Tool to calculate the emission factor for an electricity system".. b. Official grid emission factors published by host country governments c. Grid emission factors published as CDM standardized baseline approved by the CDM Executive Board.
Measurement procedures (if any):	-
Any comment:	The value of grid emission factor shall be updated at the time of renewal of the Project crediting period.

Parameter ID	**CSAC 12**
Data / Parameter:	$EF_{solvent}$
Data unit:	t CO_2-eq./t solvent
Description:	Emission factor of solvent used for the indirect mineral carbonation process

Source of data:	The emission factor can be sourced from third party published databases (e.g. Ecoinvent)
Measurement procedures (if any):	-
Any comment:	-

Parameter ID	**CSAC 13**
Data / Parameter:	NCV_i
Data unit:	kWh/t
Description:	Net calorific value of fuel type i, used for the operation of carbonation plant or reboiler (e.g. diesel generation for on-site electricity consumption)
Source of data:	Most recent version of IPCC Guidelines for National Greenhouse Gas Inventories
Measurement procedures (if any):	-
Any comment:	Net calorific value of fossil fuel shall be updated at the time of renewal of the project crediting period.

Parameter ID	**CSAC 14**
Data / Parameter:	$EF_{fuel,i}$
Data unit:	t CO_2-eq./GJ
Description:	Emission factor of fuel type i used for operation of carbonation plant or reboiler (e.g. diesel generation for on-site electricity consumption)
Source of data:	Most recent version of IPCC Guidelines for National Greenhouse Gas Inventories
Measurement procedures (if any):	-
Any comment:	Emission factor of fuel shall be udpated at the time of renewal the project crediting period.

Parameter ID	**CSAC 15**
Data / Parameter:	$D_{sand,baseline}$
Data unit:	Km
Description:	Average round trip distance between CRF and location of downstream use of concrete aggregate in baseline scenario. Applicable when the carbonation plant is not located at the CRF.
Source of data:	Historical records of transportation company/Facility or maps

Measurement procedures (if any):	-
Any comment:	-

5.2 | Data and parameters monitored

5.2.1 | All data collected as part of performance monitoring shall be archived electronically and be kept at least for 2 years after the end of the last crediting period. All the data should be monitored if not indicated otherwise in the tables below. All measurements shall be conducted with calibrated measurement equipment according to relevant industry standards.

5.2.2 | In addition, the monitoring provisions in the applicable tools referred to in this methodology apply.

Parameter ID	**CSAC 16**
Data / Parameter:	$MG_{y,i,d}$
Data unit:	t
Description:	Mass of the concrete aggregate type i of a grain size distribution d in monitoring period y.
Source of data:	On-site measurements.
Measurement procedures (if any):	Mass or volume-based measurements
Monitoring frequency:	Continuously, aggregated to the total amount per monitoring period
QA/QC procedures:	-
Any comment:	-

Parameter ID	**CSAC 17**
Data / Parameter:	$m_{CO_2,i,d}^{in}$
Data unit:	t CO_2
Description:	mass of CO_2 which was fed to the reactor system in within the monitoring period y
Source of data:	On-site measurements.
Measurement procedures (if any):	The gas flow rate is measured through a calibrated mass flow meter. In case the gas is not pure CO_2 (CO_2 concentration below 98%), the composition may be measured with a corresponding device. To minimize the gas loss to the atmosphere, the saturation of the material i and grain size d with respect to the CO_2 uptake is measured directly or indirectly with a sensor and the gas flow rate is adjusted correspondingly.
Monitoring frequency:	Continuously, during carbonation unit operation. Aggregated to the total amount per monitoring period

QA/QC procedures:	Measured results shall be cross checked with the amount of the Liquefied CO_2 purchased (invoices/Liquefied CO_2 trucks weight measurement records)
Any comment:	-

Parameter ID	**CSAC 18**
Data / Parameter:	$m^{out}_{CO_2,i,d}$
Data unit:	t CO_2
Description:	mass of CO_2 which is exiting the reactor system in the exiting gas stream in the monitoring period y
Source of data:	On-site measurements.
Measurement procedures (if any):	The plant shall be equipped with a device measuring the flow rate and composition of the exiting gas stream. These two numbers allow to determine the amount of CO_2 $m^{out}_{CO_2,i,d}$ (t CO_2) exiting the process in the monitoring period y
Monitoring frequency:	Continuously, during plant operation. Aggregated to the total amount per monitoring period
QA/QC procedures:	Measured results shall be cross checked with previously obtain results of other project sinks
Any comment:	-

Parameter ID	**CSAC 19**
Data / Parameter:	$y_{CO_2,i,d}$
Data unit:	Mole CO_2 /mole gas
Description:	CO_2 concentration in the void fraction between the particles of concrete aggregate during material discharge
Source of data:	On-site measurements.
Measurement procedures (if any):	Options to determine $y_{CO_2,i,d}$: A dedicated CO_2 concentration sensor measures the CO_2 concentration in the gas phase between the particles, as they are discharged from the system. This concentration is monitored over 10 representative process cycles and shall be recalibrated regularly.
Monitoring frequency:	Measured annually in industrial operation
QA/QC procedures:	-
Any comment:	This value has to be validated on a recurring basis

Parameter ID	**CSAC 20**
Data / Parameter:	$D_{CO2,f,y}$
Data unit:	km
Description:	Round trip distance between liquefaction plant and CRF for each freight (Delivery) of liquefied CO_2

Source of data:	Records of transportation company/Facility or maps
Measurement procedures (if any):	-
Monitoring frequency:	For each truck, delivered liquefied CO_2 to CRF
QA/QC procedures:	-
Any comment:	-

Parameter ID	**CSAC 21**
Data / Parameter:	$F_{RCO2,f,y}$
Data unit:	Tonne
Description:	Total mass of freight (Liquefied CO_2) transported in each freight transportation activity f in the monitoring period y
Source of data:	Records of transportation company/Facility
Measurement procedures (if any):	Options to determine $F_{RCO2,f,y}$: • Measured with a flow meter at the inlet/outlet of the CO_2 storage tank. • With scales • Measurement of the CO_2 level in the gas storage tank
Monitoring frequency:	For each truck, delivered liquefied CO_2 to CRF
QA/QC procedures:	Measured mass of delivered liquefied CO_2 shall be cross-checked with the invoiced amounts.
Any comment:	-

Parameter ID	**CSAC 22**
Data / Parameter:	$D_{CA,e,y}$
Data unit:	km
Description:	Round trip distance between CRF and carbonation plant. Only has to be considered when the carbonation plant is not located at the CRF.
Source of data:	Records of transportation company/Facility or maps
Measurement procedures (if any):	-
Monitoring frequency:	For each truck
QA/QC procedures:	-
Any comment:	-

Parameter ID	**CSAC 23**
Data / Parameter:	$F_{CA,e,y}$
Data unit:	Tonne

Description:	Total mass of freight (concrete aggregate (CA)) transported in each freight transportation activity e in the monitoring period y. Only has to be considered when the carbonation plant is not located at the CRF.
Source of data:	Records of transportation company/Facility
Measurement procedures (if any):	Mass or volume-based measurements
Monitoring frequency:	For each truck, delivered concrete aggregate from CRF to the carbonation plant.
QA/QC procedures:	-
Any comment:	-

Parameter ID	**CSAC 24**
Data / Parameter:	$D_{CCA/sand,g,y}$
Data unit:	km
Description:	Round trip distance between carbonation plant and location of downstream use of the carbonated concrete aggregate or regenerated sand. Only has to be considered when the carbonation plant is not located at the CRF.
Source of data:	Records of transportation company/Facility or maps
Measurement procedures (if any):	-
Monitoring frequency:	For each truck
QA/QC procedures:	-
Any comment:	-

Parameter ID	**CSAC 25**
Data / Parameter:	$FR_{CCA/sand,g,y}$
Data unit:	Tonne
Description:	Total mass of freight (carbonated concrete aggregate or regenerated sand) transported in each freight transportation activity g in the monitoring period y. Only has to be considered when the carbonation plant is not located at the CRF.
Source of data:	Records of transportation company/Facility
Measurement procedures (if any):	Mass or volume-based measurements
Monitoring frequency:	For each truck, delivered carbonated concrete aggregate or regenerated sand from carbonation plant to the location of downstream use

QA/QC procedures:	-
Any comment:	-

Parameter ID	**CSAC 26**
Data / Parameter:	$EC_{carbonation,y}$
Data unit:	MWh
Description:	Electricity Consumption of CO_2 carbonation process in monitoring period y
Source of data:	Electric meter on-site
Measurement procedures (if any):	-
Monitoring frequency:	Continuously over the monitoring period y
QA/QC procedures:	-
Any comment:	For determination of ex-ante emission reductions, the specific electricity consumption of the carbonation plant shall be used.

Parameter ID	**CSAC 27**
Data / Parameter:	$FC_{carbonation,i,y}$
Data unit:	Tonne
Description:	Consumption of fossil fuel(s) i for on-site power generation for carbonation process in monitoring period y
Source of data:	On site measurements
Measurement procedures (if any):	-
Monitoring frequency:	Continuously
QA/QC procedures:	To be cross-checked with fuel purchase invoices.
Any comment:	-

Parameter ID	**CSAC 28**
Data / Parameter:	$FC_{evaporation,i,y}$
Data unit:	Tonne
Description:	Consumption of fossil fuel(s) i for on-site power or heat generation for evaporation process in monitoring period y
Source of data:	On site measurements
Measurement procedures (if any):	-
Monitoring frequency:	Continuously
QA/QC procedures:	To be cross-checked with fuel purchase invoices.
Any comment:	-

Parameter ID	**CSAC 29**
Data / Parameter:	$EC_{evaporation,y}$
Data unit:	MWh
Description:	Electricity Consumption of CO_2 evaporation process in monitoring period y
Source of data:	Electric meter on-site
Measurement procedures (if any):	-
Monitoring frequency:	Continuously over the monitoring period y
QA/QC procedures:	For determination of ex-ante emission reductions, the specific electricity consumption of the reboiler shall be used which is listed in the fact sheet of the reboiler.
Any comment:	-

Parameter ID	**CSAC 30**
Data / Parameter:	$FC_{crusher,i,y}$
Data unit:	Tonne
Description:	Consumption of fossil fuel(s) i for on-site power generation for additional crushing process in monitoring period y
Source of data:	On site measurements
Measurement procedures (if any):	-
Monitoring frequency:	Continuously
QA/QC procedures:	To be cross-checked with fuel purchase invoices.
Any comment:	-

Parameter ID	**CSAC 31**
Data / Parameter:	$EC_{crusher,y}$
Data unit:	MWh
Description:	Electricity Consumption of additional crushing process in monitoring period y
Source of data:	Electric meter on-site
Measurement procedures (if any):	-
Monitoring frequency:	Continuously over the monitoring period y
QA/QC procedures:	For determination of ex-ante emission reductions, the specific electricity consumption of the crusher shall be used
Any comment:	-

Parameter ID	**CSAC 32**
Data / Parameter:	$FC_{capture,i,y}$
Data unit:	Tonne
Description:	Consumption of fossil fuel(s) i for on-site power and heat generation for the capture, separation and collection process in monitoring period y
Source of data:	On site measurements
Measurement procedures (if any):	-
Monitoring frequency:	Continuously
QA/QC procedures:	To be cross-checked with fuel purchase invoices.
Any comment:	-

Parameter ID	**CSAC 33**
Data / Parameter:	$EC_{capture,y}$
Data unit:	MWh
Description:	Electricity Consumption of capture, separation and collection process in monitoring period y
Source of data:	Electric meter on-site
Measurement procedures (if any):	-
Monitoring frequency:	Continuously over the monitoring period y
QA/QC procedures:	For determination of ex-ante emission reductions, the specific electricity consumption of the capture, separation and collection process shall be used
Any comment:	-

Parameter ID	**CSAC 34**
Data / Parameter:	$FC_{liquefaction,i,y}$
Data unit:	Tonne
Description:	Consumption of fossil fuel(s) i for on-site power generation for the liquefaction in monitoring period y
Source of data:	On site measurements
Measurement procedures (if any):	-
Monitoring frequency:	Continuously
QA/QC procedures:	To be cross-checked with fuel purchase invoices.
Any comment:	-

Parameter ID	**CSAC 35**
Data / Parameter:	$EC_{liquefaction,y}$
Data unit:	MWh

Description:	Electricity Consumption of liquefaction process in monitoring period y
Source of data:	Electric meter on-site
Measurement procedures (if any):	-
Monitoring frequency:	Continuously over the monitoring period y
QA/QC procedures:	For determination of ex-ante emission reductions, the specific electricity consumption of the liquefaction shall be used
Any comment:	-

Parameter ID	**CSAC 36**
Data / Parameter:	$FC_{ref,CO_2,i,y}$
Data unit:	Tonne
Description:	Consumption of fuel type i in year y used for the refrigerating effort of the CO_2 tank
Source of data:	On site measurements
Measurement procedures (if any):	-
Monitoring frequency:	Continuously
QA/QC procedures:	To be cross-checked with fuel purchase invoices.
Any comment:	-

Parameter ID	**CSAC 37**
Data / Parameter:	$EC_{ref,CO_2,y}$
Data unit:	MWh
Description:	Electricity Consumption of CO_2 tank in monitoring period y (MWh)
Source of data:	Electric meter
Measurement procedures (if any):	-
Monitoring frequency:	Continuously over the monitoring period y
QA/QC procedures:	For determination of ex-ante emission reductions, the specific electricity consumption of the CO_2 tank shall be used
Any comment:	-

Parameter ID	**CSAC 38**
Data / Parameter:	$SC_{solvent,y}$
Data unit:	Kg solvent
Description:	Solvent Consumption of the indirect mineral carbonation process

Source of data:	On-site measurements.
Measurement procedures (if any):	Using scales or flow meters on-site
Monitoring frequency:	Continuously
QA/QC procedures:	Cross check with transport bills
Any comment:	-

Parameter ID	**CSAC 39**
Data / Parameter:	$CO_{2,biogenic}$
Data unit:	Tonne
Description:	Amount of CO_2 that originated from biogenic waste or DAC.
Source of data:	Invoices, Monitoring and Reporting regulations of the European Emission Trading scheme or equivalent (EUR-Lex - 02018R2066-20210101 - EN - EUR-Lex (europa.eu), on site measurements
Measurement procedures (if any):	-
Monitoring frequency:	For all the CO_2 which is used for the carbonation process.
QA/QC procedures:	-
Any comment:	Methodology only applicable, when the sequestered CO_2 originated from biogenic waste or DAC. If this is not the case, CO_2 removal cannot be claimed under this methodology.

Parameter ID	**CSAC 40**
Data / Parameter:	$Sink_{CaCO3}$
Data unit:	Tonne
Description:	Amount of $CaCO_3$ used as filler material in the construction sector or in other applications that ensure the permanent storage of CO_2
Source of data:	Invoices, records
Measurement procedures (if any):	-
Monitoring frequency:	For all the $CaCO_3$ produced with the indirect mineral carbonation process in the monitoring period y
QA/QC procedures:	-
Any comment:	If there is no verification of the type of application of the $CaCO_3$, the storage of the CO_2 is assumed to be non-permanent by default and no VERs are issued for the sequestered CO_2.

Parameter ID	**CSAC 41**
Data / Parameter:	End use distribution
Data unit:	-
Description:	The distribution of various end uses of concrete aggregate monitored
Source of data:	Sales invoices, sales records or any other valid sources
Measurement procedures (if any):	The project developer shall assess the distribution of various end uses of concrete aggregate produced by the project/activity (i.e., use in road construction, concrete structures, residential and commercial landscaping etc.) and disclose it in the Monitoring Report.
Monitoring frequency:	Continuously
QA/QC procedures:	-
Any comment:	The VVB shall, based on its sectoral expertise and means of verification, assess the ability of reported end use types in regard to ensuring CO_2 permanence and provide their opinion in the Verification Report. The Certification Body shall review the information provided by the project developer and the VVB's opinion and act accordingly.

6| APPLICATION TO PROGRAMME OF ACTIVITIES

6.1.1 | The methodology may be applied for standalone project or program of activities (PoAs). In the latter case, the technology provider(s) may act as Coordinating and Managing Entity (CME). For inclusion of VPA to the PoA, the inclusion criteria shall be designed following the methodology requirements and other applicable standard requirements.

7| List of references

i. Tiefenthaler, J., Braune, L., Bauer, C., Sacchi, R. and Mazzotti, M. (in press). Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector

8| Supplementary information

8.1 | Calcination & Carbonation process

Cement is produced in a rotary kiln at high temperatures of 1400 to 1500°C. Limestone ($CaCO_3$) is converted into calcium oxide (CaO) by calcination (i.e., high temperature burning of the mineral raw material ($CaCO_3$)). As a result, CO_2 is separated and released to the atmosphere. The following formula describes the chemical process of calcination:

$$CaCO_3 \leftrightarrows CaO + CO_2 \qquad \textit{Eq. 19}$$

When concrete is produced from cement, the calcium oxide present in the cement hardens by adding water via an exothermic reaction to form calcium hydroxide and calcium silicate hydrate (C-S-H).

$$CaO + H_2O \leftrightarrows Ca(OH)_2 \qquad \textit{Eq. 20}$$

Once the concrete is hardened, the calcium hydroxide ($Ca(OH)_2$) formed in formula (Eq 20) can again react with CO_2 to form the calcium carbonate ($CaCO_3$) occurring in formula (Eq 21), provided that the salt $CaCO_3$ exhibits the lowest solubility of all salts in the H_2O – CO_2 – Ca system. This process is called "carbonation":

$$Ca(OH)_2 + CO_2 \leftrightarrows CaCO_3 + H_2O \qquad \textit{Eq. 21}$$

Normally, this happens only on the surface of the hardened concrete components over the typical lifetime of 80 years. An experimental field study conduced at the Federal Swiss Institute of Technology in Zurich came to the conclusion that around 4% of the process emissions are bound over the lifetime of a concrete infrastructure[5].

However, this process can be accelerated and increased with the direct and indirect mineral carbonation. The mineral carbonation processes use higher CO_2 concentrations than average atmospheric values of 400 ppm, humidity, temperature, solvents and optimised particle size of the concrete to accelerate the process of carbonation. This is where the proposed technologies and project activities can be applied.

8.2 | Technologies

In the scope of this methodology, two technologies are described. However, this methodology may also be applicable for future systems, which fall into the same category and where the presented calculation and measurement methods can be applied.

a. Direct Mineral Carbonation

This process sequesters carbon in a recycling product – concrete aggregate a material stream containing cement. Through the applied process, concrete aggregate is exposed directly to a gas stream exhibiting an increased CO_2 concentration (>400 ppm) in a reactor system (carbonation plant) at controlled pressure. The calcium hydroxide ($Ca(OH)_2$) and C-S-H, originally contained in

[5] Birolini, L. (2019). CO_2 capture in concrete recycling residues. Master Thesis, 1–47

the hardened cement paste react with the CO_2 to form chemically stable calcium carbonate ($CaCO_3$). The product of this process is carbonated concrete aggregate.

b. Indirect Mineral Carbonation

In a first step, the concrete aggregates are suspended in a solvent in the dissolution reactor. The solvent selectively extracts the calcium contained in the hydrated cement phases. In a next step, the inert materials, termed regenerated sand, are filtered out of the slurry and the calcium-enriched solution is fed to the mineralization reactor.

There, the solution is brought into contact with CO_2 which results in the crystallization of $CaCO_3$. Finally, the precipitated $CaCO_3$ is filtered out for further use. The solution is recycled into the dissolution reactor. The solvent lost is compensated with a makeup stream of fresh solvent. The regenerated sand can be used as a replacement for sand in concrete, in road construction or it can be landfilled. There are different potential applications for the produced $CaCO_3$ such as using it as filler material in cement or concrete. Moreover, it can be used in the food industry or as an additive in cleansing material.

Carbonation is an exothermic process and releases heat. The reverse reaction, calcination, requires a lot of energy. Unless the $CaCO_3$ is exposed to temperature above 900°C, the CO_2 is permanently stored in both processes.

The source of the CO_2 shall be biogenic waste such as (but not limited to) sewage sludge and animal manure. However, a project using non-biogenic sources of CO_2 (originating from industrial processes) may apply this methodology by proposing any suitable revisions to this methodology. If the emissions along the value chain of the CO_2 mineralization are smaller than the amount of CO_2 stored, these processes generate negative greenhouse gas emissions. The projects thus act as geological sinks.