LIFE CYCLE ASSESSMENT OF LIMENET COMBINED WITH DIRECT AIR CAPTURE (LIMENET-DAC) PROCESS FOR REMOVING AND STORING ATMOSPHERIC CO_2

Francesco Pietro Campo, Stefano Caserini, Mario Grosso

Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci, 22 (Milano, Italia)

Email address: francescopietro.campo@polimi.it

Introduction

LIMENET is a technology for capturing and storing CO_2 in the form of bicarbonate ions (HCO_3^-) in the sea using slaked lime ($Ca(OH)_2$). The chemical background of the process is the same of Buffered Accelerated Weathering of Limestone (BAWL) presented by Caserini et al. (2021). Instead of BAWL, the benefit of LIMENET process consists in the use of only slaked lime which reacts faster with CO_2 forming HCO_3^- avoiding the installation of long submarine pipeline necessary for the slow dissolution of $CaCO_3$ in the seawater. Thus, LIMENET stores CO_2 coming from the calcination of calcium carbonate for the production of slaked lime. A portion of slaked lime is used for storing CO_2, the remaining one can be used as it is since it is a valuable product or can be used for producing negative emissions since it is a component of Negative Emission Technologies (NETs) such as ocean liming or Direct Air Capture (DAC).

LIMENET process is a method for storing CO_2 that allows to obtain negative emission if CO_2 is removed from the atmosphere combining LIMENET with a system of DAC (LIMENET-DAC). Furthermore, LIMENET-DAC is a fine combination of technologies since decarbonized slaked lime can be used for the regeneration of the sorbent when aqueous hydroxide sorbent such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) are used for capturing CO_2 directly from the air and at the same time LIMENET provides a way for storing CO_2.

In this report, the potential environmental impacts of the NET LIMENET-DAC are evaluated using Life Cycle Assessment (LCA) methodology standardized by the ISO norms 14040 and 14044 (ISO, 2006a; 2006b). LCA applied to LIMENTE-DAC will be presented following the phases of LCA:

- **Goal and scope** where the aim of the study, the functional unit (FU), the system boundary, the selected impact categories and the main assumptions are presented;
- **Life cycle inventory** where the material and energy consumptions of the process are expressed per FU;
- **Life cycle impacts assessment** where the potential environmental impacts will be analysed;
- **Interpretation**, LCA phase applied that during the whole study to guarantee that LCA is coherent with the defined goal and scope and the inventory is complete and proper for the study aim, and to analyse the results of LCA.

Goal and scope

The aim of the study is to assess the potential environmental impacts of the NET LIMENET-DAC according to LCA methodology through a “cradle to grave” approach. Special focus on overall potential greenhouse gas (GHG) emissions is given in order to assess the efficacy and the efficiency of LIMENET-DAC, i.e., negative emissions are achieved and how much respectively. In addition to Climate change impact, the potential impacts in other 15 impact categories (resumed in Table 1) are assessed applying Environmental Footprint (EF) method implemented in SimaPro software.

The potential impacts and the material and energy data of the process are referred to the Functional Unit (FU) which should represents the function of the process. In this LCA, 1 tonne of CO_2 captured directly from the air and stored in the form of HCO_3^- in the sea is chosen as FU.

The analysed process for capturing CO_2 from the air uses KOH aqueous solution as developed by Carbon Engineering (Keith et al., 2018) while the process for storing CO_2 is LIMENET. The mass and energy flows are reported in Figure 1, where the system boundaries of the study through LCA are shown.

Table 1. Impact categories of EF method with their impact category indicator and impact category characterization model for the impacts assessment.

	Impact category	**Impact category indicator**	**Impact category characterization model**
1	Climate change	kg CO_2 eq	Bern model – Global Warming Potentials (GWPs) over a 100-year time horizon (IPCC, 2013)
2	Ozone depletion	kg CFC-11 eq	EDIP model based on the Ozone Depletion Potentials (ODP) of the World Meteorological Organization (WMO) over an infinite time horizon (WMO, 1999)
3	Ionising radiation, HH	kBq U_{235} eq	Human Health effect (Dreicer et al., 1995)
4	Photochemical ozone formation, HH	kg NMVOC eq	LOTOS-EUROS (Van Zeim et al., 2008)
5	Respiratory inorganics	disease inc.	PM method (Fantke et al., 2016)
6	Non-cancer human health effects	CTUh	USEtox (Rosenbaum et al., 2008)
7	Cancer human health effects	CTUh	USEtox (Rosenbaum et al., 2008)
8	Acidification terrestrial and freshwater	mol H^+ eq	Accumulated Exceedance (Seppälä et al., 2006; Posch et al., 2008)
9	Eutrophication freshwater	kg P eq	EUTREND (Struijs et al., 2009)
10	Eutrophication marine	kg N eq	EUTREND (Struijs et al., 2009)
11	Eutrophication terrestrial	mol N eq	Accumulated Exceedance (Seppälä et al., 2006; Posch et al., 2008)
12	Ecotoxicity freshwater	CTUe	USEtox (Rosenbaum et al., 2008)
13	Land use	Pt	CFs set re-calculated by JRC starting from LANCA® v 2.5 as baseline model. (Bos et al., 2016)
14	Water scarcity	m^3 depriv.	Available Water Remaining (Boulay et al., 2016)
15	Resource use, energy carriers	MJ	ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
16	Resource use, mineral and metals	kg Sb eq	ADP for mineral and metal resources, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).

Life cycle inventory

The mass and energy flows of the process (represented in Figure 1) are provided by the process designers. Further data are collected from other LCA studies on DAC (Deutz and Bardow, ; de Jonge et al., 2019) and Ecoinvent (version 3.5) database. In Table 2, data and Ecoinvent processes are reported.

The analysed system is assumed at TRL9 producing 1 $MtCO_2$ per year working 8300 hours for 25 years.

Figure 1. LIMENET-DAC scheme and system boundaries provided by the process designers (data are expressed per FU).

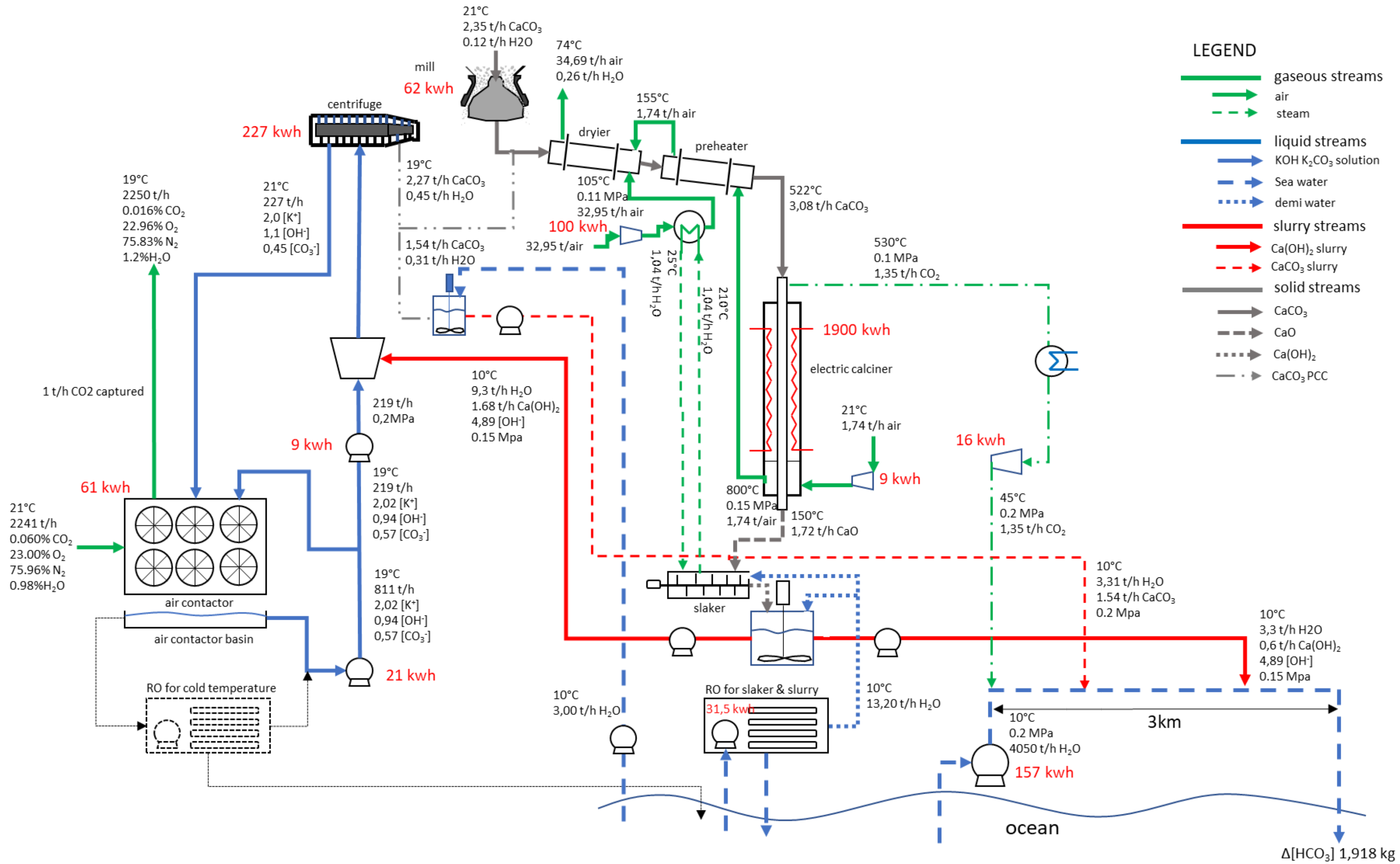


Table 2. Life cycle inventory of LIMENET-DAC.

Process phase	Ecoinvent process	Amount per FU	Note	Source
Electricity consumption	Electricity, medium voltage	2572.6 kWh	Data from Figure 1	Ecoinvent 3.5
Water supply	Tap water	0.56 t	Water necessary for slaked lime production calculated from stoichiometry	Ecoinvent 3.5
Limestone supply	Limestone, unprocessed | limestone quarry operation	2.35 t	Including blasting material, land transformation, diesel for operating condition, particulate matter emission.	Ecoinvent 3.5
Limestone transport	Transport, freight, lorry, unspecified	47 tkm	Assumed 20 km.	Ecoinvent 3.5
KOH supply	Potassium hydroxide	1 kg	Assuming KOH used as sorbent for capturing CO_2 directly from the air due to efficiency of regeneration process.	Keith et al. (2018)
LIMENET-DAC plant	Reported in Table 3			

Table 3. Life cycle inventory of LIMENET-DAC plant.

Machine	Ecoinvent process	Amount per FU	Note	Source
Mill	Limestone, crushed, washed | production	2.35 kg	Without limestone and energy input only construction material	Ecoinvent 3.5
Calciner	Industrial machine, heavy, unspecified | production	1.59E-5 kg	Calculated on the basis of the calcium oxide per FU exiting from the calciner	Ecoinvent 3.5
Slaker	Industrial machine, heavy, unspecified | production	2.00E-4 kg	Calculated on the basis of the slaked lime per FU exiting from the slaker	Ecoinvent 3.5
Pumps	Pump, 40W| production	7.37E-2 p	Considering a plant capturing operating 8400h/y for 25 years	Ecoinvent 3.5
Compressors	Compressor, gas turbine 10MW electrical	2.41E-8 p	Considering a plant capturing operating 8400h/y for 25 years	Koornneef et al. (2008)
Pipeline	Polyethylene, high density, granulate	1.34E-3 kg	Assuming a commercial HDPE pipeline length 3 km, outer diameter 2500, inner diameter 2378	Ecoinvent 3.5
	Extrusion, plastic pipes	1.34E-3 kg		Ecoinvent 3.5
Air contactor	Polyvinylchloride, bulk polymerised	0.76 kg	PVC	de Jonge et al. (2019)
	Polypropylene, granulate	0.833 g	Polypropylene	de Jonge et al. (2019)
	Steel, chromium steel 18/8, hot rolled	1.72 g	Stainless steel	de Jonge et al. (2019)
	Steel, low-alloyed, hot rolled	269 g	Low-alloyed steel	de Jonge et al. (2019)
	Polyurethane, rigid foam	3.79 g	Polyurethane	de Jonge et al. (2019)
	Glass fibre reinforced plastic, polyamide, injection moulded	6.31 g	Glass fibre	de Jonge et al. (2019)
	Concrete, normal	6.68E-3 m^3	Concrete	de Jonge et al. (2019)

Life cycle impact assessment

The potential impacts are calculated assuming current Italian and Norwegian energy mix because currently because there is a lab-plant located in La Spezia (Italy) and a pilot plant will be realized in Norway. The results are shown in Table 4 and the comparison of the total impacts expressed as percentage of the maximum impact is reported in Figure 2. The results show that the potential impacts are much lower, at least of 50%, with Norwegian electricity mix than with Italian electricity mix, because the current Italian electricity mix is characterized by fossil fuels while the Norwegian one by renewable (see Table 5).

Table 4. Total of all impact categories.

	Impact category	**Unit of measure (UOM)**	**Total (UOM/FU)**	
			Italy	**Norway**
1	Climate change	kg CO_2 eq	1066	68
2	Ozone depletion	kg CFC-11 eq	1,44E-04	2,35E-06
3	Ionising radiation, HH	kBq U_{235} eq	145	45
4	Photochemical ozone formation, HH	kg NMVOC eq	2,30	0,15
5	Respiratory inorganics	disease inc.	1,76E-05	2,32E-06
6	Non-cancer human health effects	CTUh	5,86E-05	9,55E-06
7	Cancer human health effects	CTUh	6,76E-06	3,54E-06
8	Acidification terrestrial and freshwater	mol H^+ eq	4,79	0,21
9	Eutrophication freshwater	kg P eq	0,239	0,022
10	Eutrophication marine	kg N eq	0,74	0,05
11	Eutrophication terrestrial	mol N eq	8,2	0,5
12	Ecotoxicity freshwater	CTUe	227	57
13	Land use	Pt	5417	1061
14	Water scarcity	m^3 depriv.	734	91
15	Resource use, energy carriers	MJ	16077	1069
16	Resource use, mineral and metals	kg Sb eq	1,18E-03	5,73E-04

Figure 2. Comparison of the total impacts expressed as percentage of the maximum impact (number on x-axis indicates the respective impact category as numbered in Table 4).

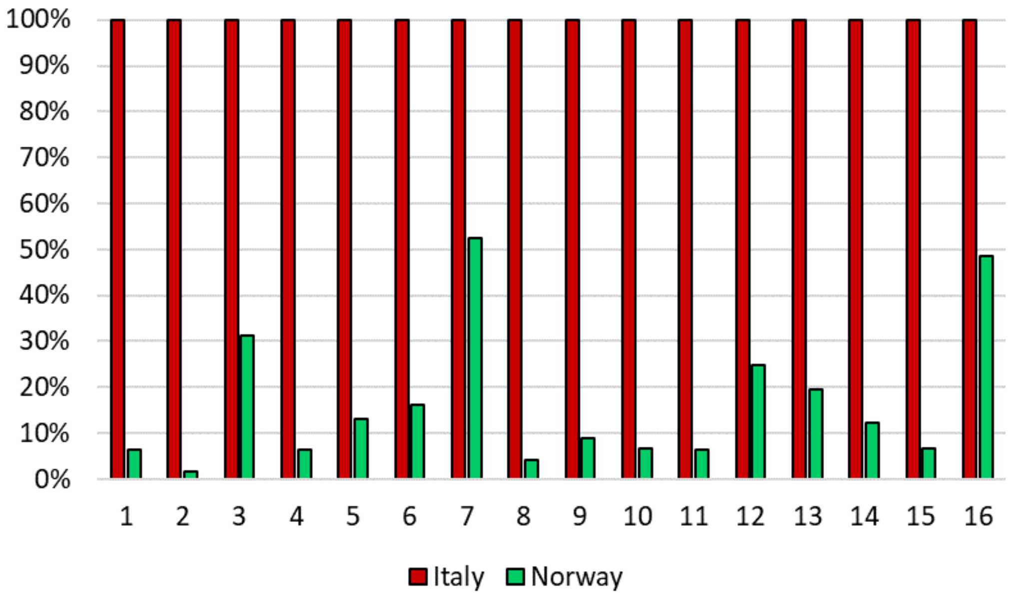


Table 5. Energy sources for electric production in Italy and Norway from Ecoinvent database based on IEA (2017) data.

Energy source	Italy	Norway
Geothermic	2%	-
Hydroelectric	21%	92%
Wind	6%	2%
Fossil	54%	2%
Imported	17%	4%

From the contribution analysis, where the contribution of the process phase to each impact is reported in Figures 3 and 4, the electricity mix results the most impacting phase in particular in Climate change impact category. Thus, a sensitivity analysis on the effect of the electricity emission factor on the carbon dioxide removal efficiency will be presented.

The carbon dioxide removal efficiency (E_{CDR}) expressed as percentage is defined as the following equation.

$$E_{CDR}(\%) = \frac{(Climate\ change\ total\ impact) - CDR}{CDR} \times 100$$

Where *Climate change total impact* is the total impact in that category, i.e., life cycle GHG emission of LIMENET-DAC, and *CDR* is the amount of atmospheric CO_2 removed by the plant, i.e., 1 tonne of CO_2

Figure 5 shows how E_{CDR} changes according to the electricity emission factor. Higher emission factor implies lower emission factor, e.g., with an electricity emission factor similar to the Italian one (around 407 gCO_2eq/kWh) E_{CDR} is negative, i.e., the life cycle GHG emission of LIMENET-DAC process is higher than the amount of removed CO_2. Meanwhile, lower electricity emission factor allows to achieve negative emission with high efficiency, e.g., with the Norwegian electricity emission factor E_{CDR} is around 93%, i.e., about 7% of removed CO_2 offsets the life cycle GHG emission of LIMENET-DAC and around 930 $kgCO_2$ per tonne of removed CO_2 are net negative emission.

Figure 3. Contribution analysis of Italian electricity mix scenario (number on x-axis indicates the respective impact category as numbered in Table 4).

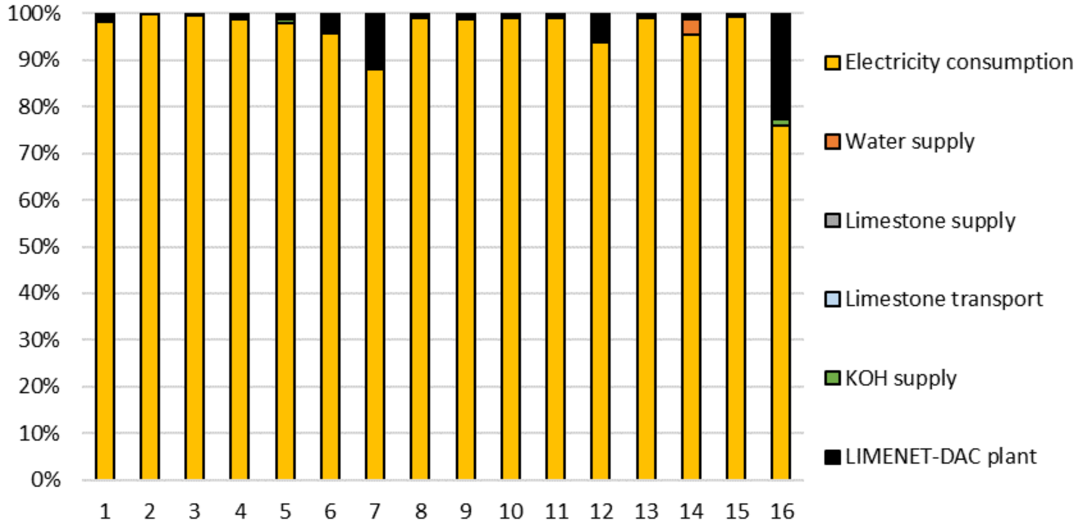


Figure 4. Contribution analysis of Norwegian electricity mix scenario (number on x-axis indicates the respective impact category as numbered in Table 4).

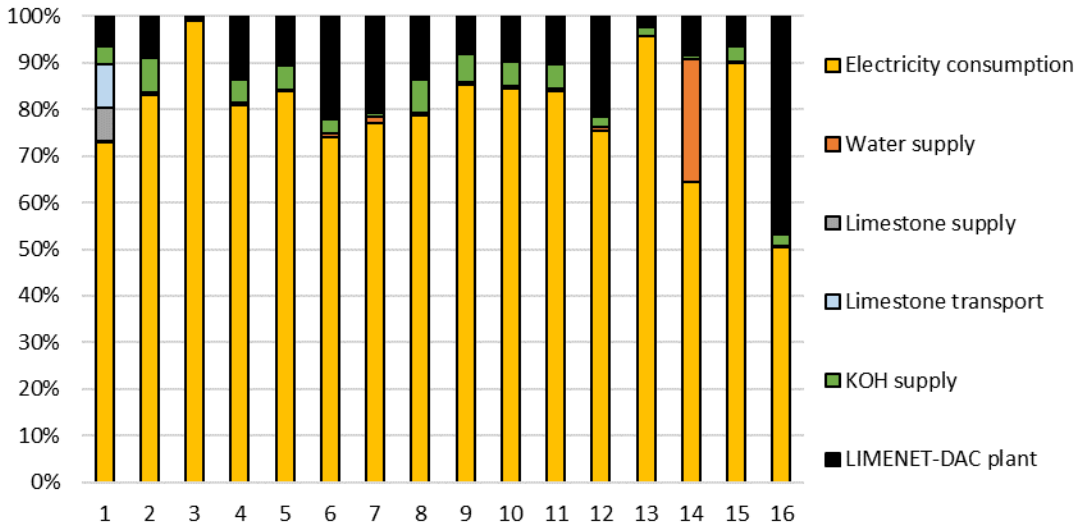
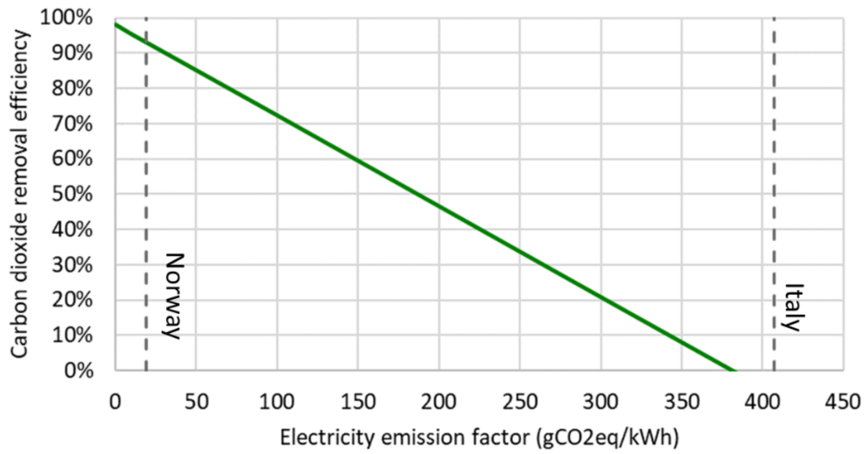


Figure 5. E_{CDR} change according to the electricity emission factor.



Process flow diagram (PFD) of LIMENET-DAC

Here are represented different process flow diagram (PFD) of LIMENET-DAC (Norwegian case) different technology stages: TRL7 and TRL9. With figure 6 and 7 it is possible to visualize the project emissions numbers above. Note how TRL7 has higher emission ratio, i.e., life cycle process GHG emission over 1 t of removed CO_2, (8.5%) than TRL9 (6.7%). This is due to economy of scale. The life cycle GHG emissions for TRL 7 are estimated from the TRL9 ones. The TRL7 construction materials emissions are rescaled proportionally to project size, i.e. 1000 tCO_2 per year working 5 years, while the other process phases emissions are similar to TRL9 process because they are operational consumption (limestone, KOh, water and electricity) that are assumed not be affected by economy of scale.

Norwegian case of LIMENET-DAC at TRL7 corresponds to project proposal.

Figure 6. PFD LIMENET - DAC TRL7.

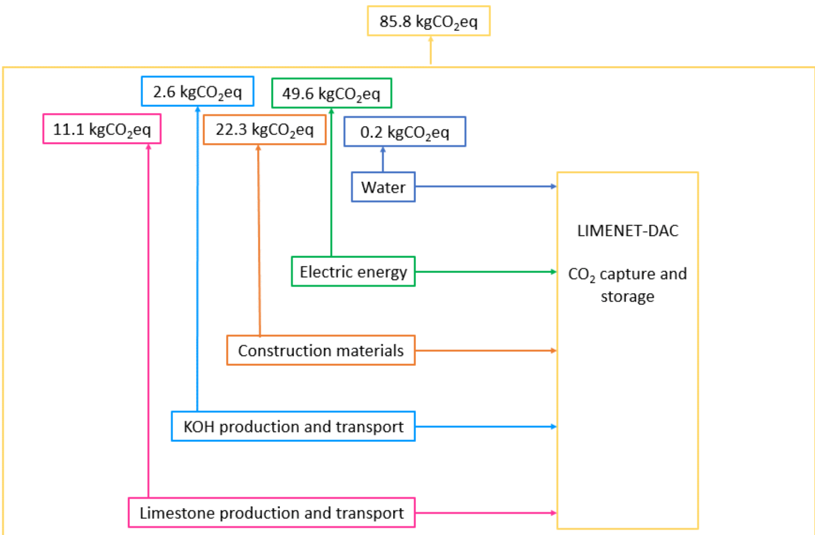
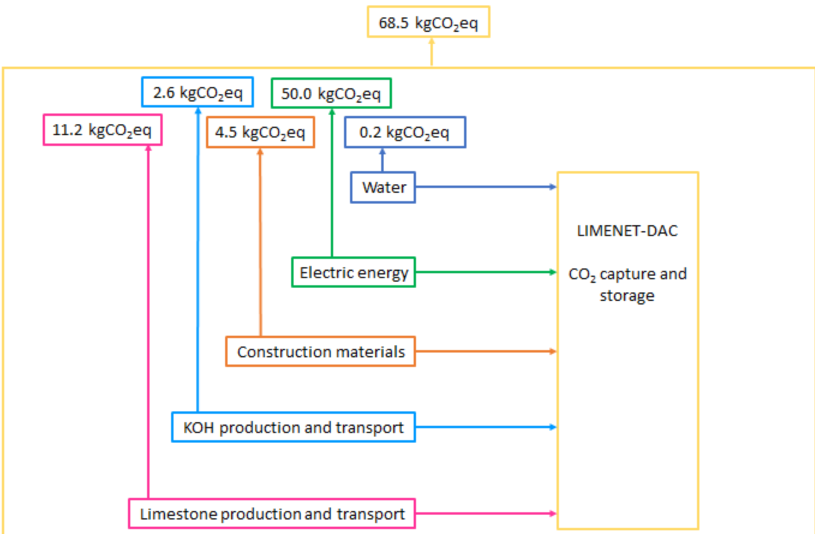


Figure 7. PFD LIMENET - DAC TRL9.



Conclusions

This LCA study evaluates the potential environmental impacts of LIMENET-DAC process that captures CO_2 from the air using KOH as studied by Keith et al. (2018) and stores it in the sea as bicarbonate (Caserini et al., 2021).

The results show that the most impacting phase particularly on climate change is the electricity consumption. Thus, the electricity source is pivotal to obtain negative emission. Electricity produced from renewable energy source allows to achieve high rate of carbon dioxide removal efficiency, i.e., only around 6% of the removed CO_2 is necessary to offset life cycle GHG emissions of LIMENET-DAC process. This high rate of efficiency is already feasible in Norway where more than 90% of the electricity is currently produced from renewables.

References

Caserini et al. (2021) Buffered accelerated weathering of limestone for storing CO_2: Chemical background. International Journal of Greenhouse Gas Control, 112, 103517. DOI: 10.1016/j.ijggc.2021.103517

de Jonge et al. (2019) Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents. International Journal of Greenhouse Gas Control, 80, 25-31. DOI: 10.1016/j.ijggc.2018.11.011

Deutz and Bardow (2021) Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Nature Energy, 6, 203-213. DOI: 10.1038/s41560-020-00771-9

IEA (2017) IEA World Energy Statistics and Balances. OECD iLibrary, eISSN: 1683-4240, DOI: 10.1787/enestats-data-en

ISO (2006a) ISO 14040:2006. Environmental Management — Life Cycle Assessment — Principles and Framework (International Organization for Standardization, 2006).

ISO (2006b) ISO 14044:2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines (International Organization for Standardization, 2006).

Keith et al. (2018) A Process for Capturing CO_2 from the Atmosphere. Joule, 2, 8, 1573-1594. DOI: 10.1016/j.joule.2018.05.006

Koornneef et al. (2008) Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. International Journal of Greenhouse Gas Control, 2, 4, 448-467. DOI: 10.1016/j.ijggc.2008.06.008