Frontier

[HYROGAS SIA]

Carbon Dioxide Removal Purchase Application

Fall 2022

General Application - Prepurchase

(The General Application applies to everyone; all applicants should complete this)

Company or organization name

HYROGAS SIA

Company or organization location (we welcome applicants from anywhere in the world)

Latvia

Name(s) of primary point(s) of contact for this application

Valdis Bisters

Brief company or organization description

HYROGAS with in-house FEED capacity develops and implements innovative technologies for circular economy to meet climate and energy transition challenges.
<20 words

1. Project Overview[1]

a. Describe how the proposed technology removes CO_2 from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

1. Introduction

HYROGAS has engineered the innovative hybrid integrated technology LIMENET–DAC that is able to

[1] We use "project" throughout this template, but note that term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

remove carbon dioxide from the atmosphere and store it in form of calcium bicarbonates into seawater by mimicking and accelerating the already naturally occurring process of carbon dioxide removal performed by the natural weathering of limestone.

As part of the carbon cycle, key to earth's carbon balance, ocean absorbs and stores CO_2 from air. Acidity caused by the uptake of CO_2 is partially balanced by the ocean's weathering of carbonate rocks whose cations allow the ocean to keep its pH balanced (8.2-8.1).

This cycle, however, is too slow to keep up with humans' ever-growing emissions, as it would take hundreds of thousands of years to revert the balance back to pre-industrial level. So far, ocean pH has dropped from 8.2 to 8.1 since the industrial revolution and is expected by fall another 0.3 to 0.4 pH units by the end of the century[2].

2. The Technology

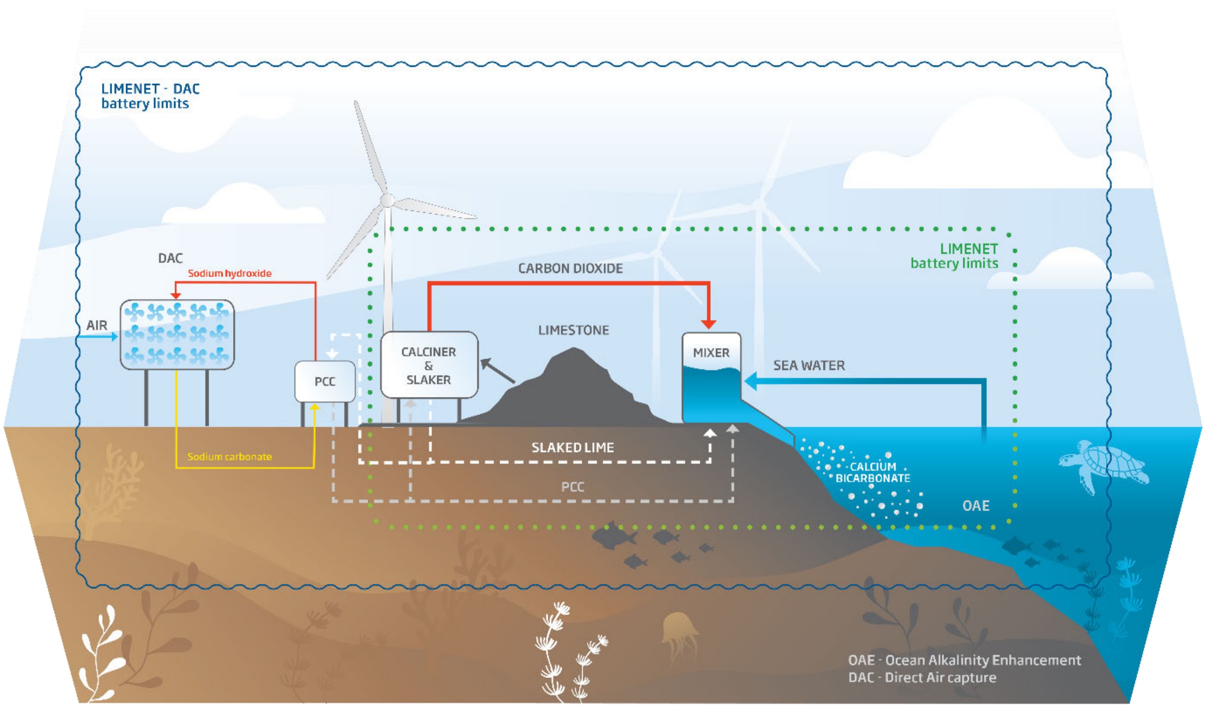

Figure 1 LIMENET-DAC.

LIMENET-DAC plant's (See Figure 1) functioning is very straightforward and can be divided into five parts:

1. **Capture** of CO_2 through the DAC air-liquid contactor;
2. **Production** of $Ca(OH)_2$ using an electric calciner;
3. **Regeneration** of the K_2CO_3 generated by the reaction of the KOH with the CO_2 using $Ca(OH)_2$: the reaction of K_2CO_3 with $Ca(OH)_2$ produces micron size precipitated $CaCO_3$ (PCC – Precipitated Calcium Carbonate) that is collected by a decanter centrifuge;

[2] https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification#section_77

4. **Storage** of the CO_2 produced by the calciner into a seawater stream in form of calcium bicarbonates, firstly dissolving the CO_2 into seawater generating an acidic seawater stream, then dissolving the PCC into the acidic seawater stream and finally buffering the remain CO_2 with $Ca(OH)_2$ and generating an ionic solution with the same pH of the surrounding seawater;
5. **Dilution** of the discharged oversaturated ionic solution into the ocean to avoid any abiotic precipitation.

2.1. Mass and Energy balance

A simplified mass and energy balance of the LIMENET-DAC process (See Figure 2) using a TRL8 KOH air contactor[3] shows that a plant capturing 1 ton/h of CO_2 from air, calcines 2,35 ton/h of "virgin" limestone, 0.73 ton/h of PCC using approximately 2.6 MWh of electric energy (including the energy required for milling the limestone, calcining, pumping the seawater inside the CO_2 absorber, for blowing air and pumping the KOH aqueous solution into the scrubber and the energy required by a decanter centrifuge for the separation of PCC);

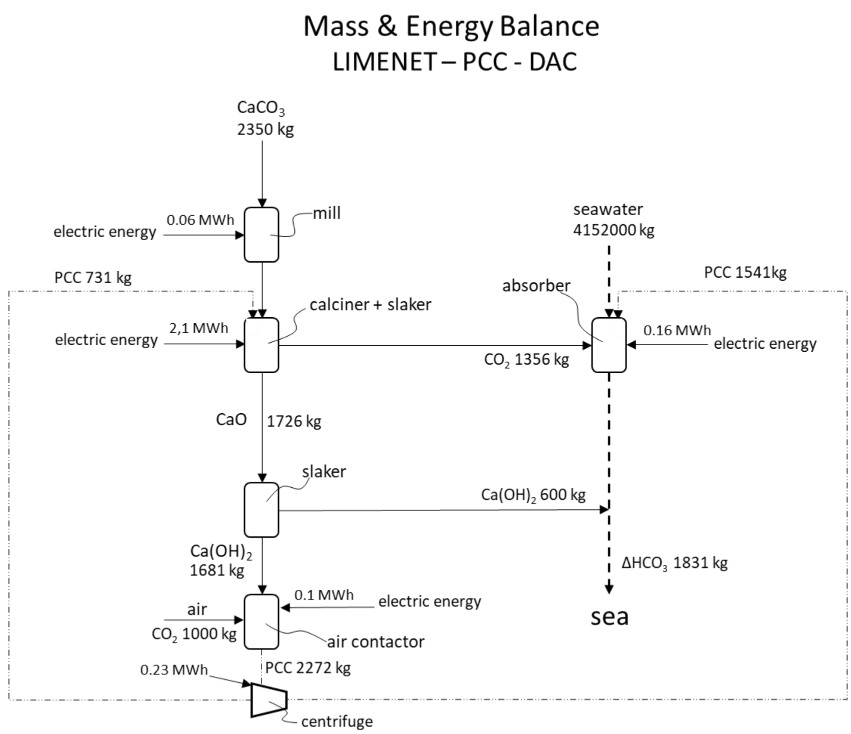

Figure 2 Simplified Mass and Energy balance.

a conservative value of 1.9 molCO_2 per mol of $Ca(OH)_2$, instead of the stoichiometric value of 2, is considered in the buffering due to the complex chemistry of the seawater.

A more complex and complete LIMENET-DAC process diagram is showed in Figure 3.

[3] Keith et al, (2018) - A process for capturing the CO2 - DOI: https://doi.org/10.1016/j.joule.2018.05.006

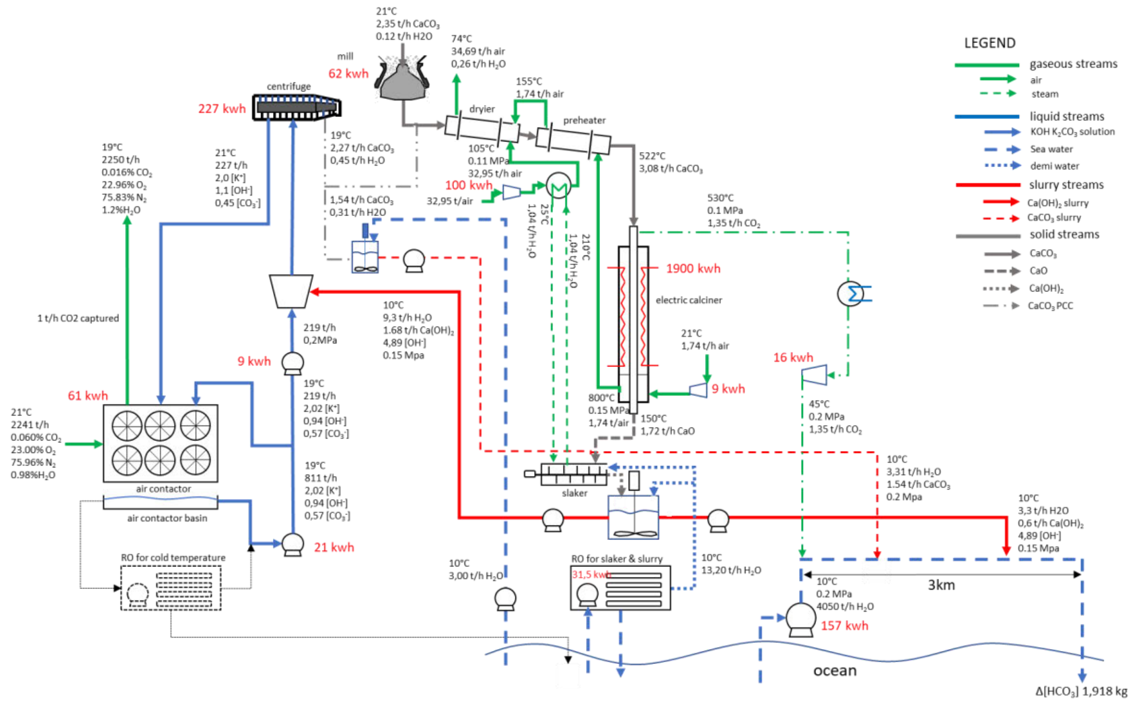

Figure 3 LIMENET - DAC Mass and Energy process diagram (high resolution rendering in TEA file)

From the Mass&Energy diagram it is possible to deduce that to capture and store 1ton of CO_2 from air the following inputs are needed:

renewable electric energy	approx. 2,6 MWh
limestone	approx. 2.5 ton
seawater	approx. 4000 ton

2.2. LIMENET-DAC process description

CO_2 is captured from air by an air-liquid contactor using a KOH solution. The reaction of the KOH solution with the CO_2 generates K_2CO_3 that is regenerated by a proper quantity of $Ca(OH)_2$ forming again KOH and precipitated $CaCO_3$ (PCC).

The $CaCO_3$ (limestone) is grinded by a mill to mm size particles, is processed by a dryer, a preheater and an electric calciner. The produced CaO is then slaked together with water to obtain $Ca(OH)_2$. The $Ca(OH)_2$ is subsequently used both for regenerating the K_2CO_3 solution and for buffering the CO_2 inside the CO_2 storage section.

The CO_2 produced by the calcination process is sent to a stream of seawater where it dissolves lowering the pH of the seawater stream. The micron-size $CaCO_3$ (PCC), is thus injected into the acidic stream of seawater where, due to the very small size, it dissolves rapidly forming $Ca(HCO_3)_2$. PCC reacts with approx. 50% of the CO_2 dissolved into the seawater stream while the remaining 50% of the CO_2 is buffered downstream by the injection of $Ca(OH)_2$ to reach the same initial pH of the seawater.

The CO_2 captured from air is temporarily stored as potassium carbonate K_2CO_3, then as calcium carbonate $CaCO_3$ and finally as calcium bicarbonate $Ca(HCO_3)_2$. In this way all the CO_2 captured from air by the DAC contactor is stored into the seawater stream as $Ca(HCO_3)_2$.

The supersaturated ionic solution is then discharged into the seawater at the same pH of natural seawaters where is diluted in the plume that will form at the discharge point. The dilution of the ionic solution with the surrounding seawater is needed to lower the supersaturation level to safe values where no abiotic precipitation can occur[4].

Once the supersaturated ionic solution is diluted with the surrounding seawaters, the storage of the CO_2 could be considered almost permanent[5],[6] . In fact, the $Ca(HCO_3)_2$ is chemically stable and lingers into the sea for hundreds of thousands of years, ensuring permanent storage of carbon dioxide[7].

2.3. LIMENET-DAC chemistry

2.3.1. Chemical's reaction LIMENET:

Equation 1 ***Weathering***

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_{2\,(aq)}$$

Equation 2 ***Buffering:***

$$CaOH_{2\,(aq)} + 2\ CO_2 \rightarrow Ca(HCO_3)_{2\,(aq)}$$

It is necessary to use seawater. Its high content in Mg^{2+} ions and organic materials can stand very high Ca^{2+} supersaturation levels for limited period of time.

2.3.2. Chemical's reaction of DAC:

Regeneration of the K_2CO_3 solution with $Ca(OH)_2$ to provide fresh KOH solution to the air-liquid contactor and PCC to the LIMENET process occurs according to the well-known reaction:

[4] Chave et al. 1970, https://doi.org/10.4319/lo.1970.15.4.0633

[5] Caldeira and Rau, 2000, https://doi.org/10.1029/1999GL002364

[6] Moras et al. (2021) Ocean Alkalinity Enhancement - Avoiding runaway CaCO3 precipitation during quick and hydrated lime dissolution - https://doi.org/10.5194/bg-2021-330

[7] https://carbonplan.org/research/cdr-verification/ocean-alkalinity-enhancement-mineral

Equation 3 ***Regeneration:***

$$K_2CO_{3(aq)}+Ca(OH)_{2(aq)} \rightarrow KOH_{(aq)}+CaCO_{3(s)}$$

where the ion K^+ could be conveniently substituted by the ion Na^+.

Absorption of CO_2 from the atmosphere occurs according to:

Equation 4 ***Absorption:***

$$2KOH_{(aq)} + CO_{2(g)} = H_2O_{(l)} + K_2CO_{3(aq)}$$

3. Alternative to other CDR technology

The LIMENET-DAC technology is a truly modular DAC with modular CO_2 storage. Many CDR technologies claim modularity (i.e. Carbon Engineering[8], Heirlom[9], Climateworks[10], Origen[11], etc.) but at the end rely on an external geological CO_2 storage that hardly can be considered modular.

The LIMENET-DAC process has the same claimed modularity of the CDR electrochemical processes with the advantage of using low-cost materials and rugged equipment for its manufacturing (i.e no electrolyzes), the absence of harmful chemicals to manage and dispose (i.e. chlorine) and an easy, problem free straightforward chemistry (i.e. no electrolysis of seawater).

Most of the LIMENET-DAC components are already well known or available in the market in the size needed for a TRL9 plant for a quick deployment of the technology.

LIMENET–DAC has a good scalability potential (see ***Confidential Addendum***) and a feasible roadmap to go close to 100 $/ton$CO_2$ if scaled to TRL9 and placed in specific low LCOE coastlines.

The LIMENET-DAC plant footprint for 1 Mton/year of CO_2 offset, is about 23 hectares plus the area needed to install the renewable electrical generation for 315 MW (i.e. onshore wind turbines).

4. LIMENET scale up

Renewable electricity sources should be used to raise the overall carbon efficiency of the process, thus windy and sunny areas are preferred, near large deposits of limestone and near coastline.

Cold climates and cold waters are preferred because of higher $CaCO_3$ solubility and less water losses due to evaporation of water in the DAC air contactor.

[8] https://carbonengineering.com/

Taking all these factors into consideration HYROGAS has chosen Norway as target location for its first plants, given the abundance of hydropower, which allows 98% of renewable energy share in the total energy mix (See Figure 4).

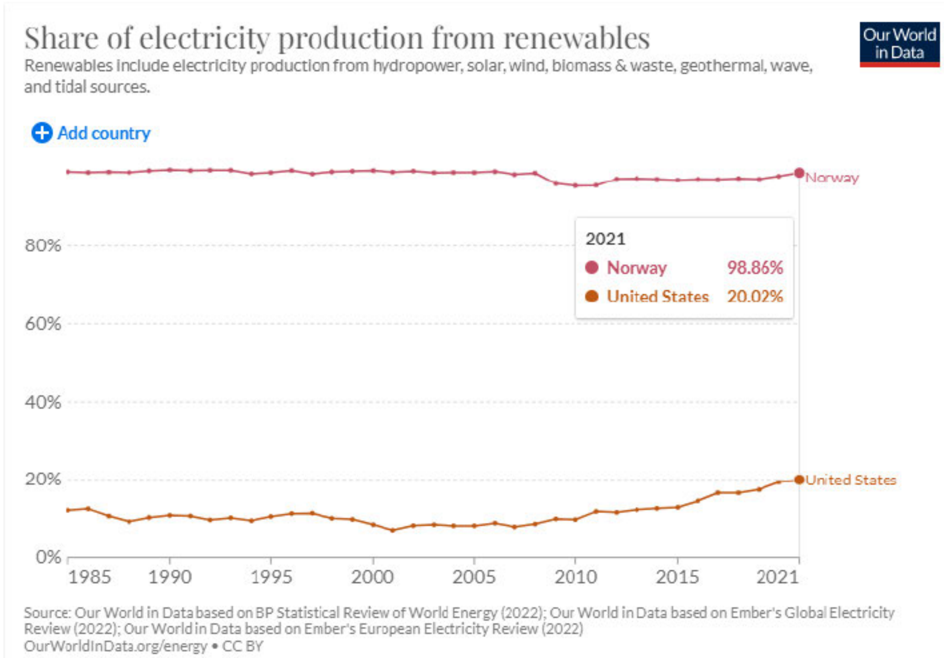

Figure 4 Norway energy mix[12].

North Norway, due to his low population, has an energy surplus which can be exploited to make LIMENET-DAC's impact minimal[13]. In fact, the average cost of the renewable electric energy in the Tromso-area in the last 20 years is 34,4€/MWh[14].

[9] https://www.heirloomcarbon.com/

[10] https://climeworks.com/

[11] https://origencarbonsolutions.com/

[12] https://ourworldindata.org/energy/country/norway

[13] https://nordkraftdc.no/greenest-cheapest/100-green-energy-article1131-1571.html

[14] https://www.nordpoolgroup.com/en/Market-data1/#/nordic/map

EUR/MWh

	Oslo	Kr.sand	Bergen	Molde	Tr.heim	Tromsø
2021	74,69	75,10	74,59	41,07	41,07	35,03
2020	9,29	9,29	9,17	9,46	9,46	8,88
2019	39,29	39,27	39,27	38,54	38,54	38,31
2018	43,65	43,25	43,05	44,08	44,08	43,71
2017	29,04	28,83	28,84	29,53	29,53	25,73
2016	26,17	25,15	24,91	28,69	28,69	25,05
2015	19,85	19,82	19,75	21,28	21,28	20,43
2014	27,33	27,23	27,14	31,54	31,54	31,44
2013	37,56	37,33	37,60	38,96	38,96	38,60
2012	29,56	29,16	28,95	31,48	31,48	31,17
2011	46,41	46,09	45,85	47,49	47,49	47,48
2010	54,25	50,82	51,79	58,04	58,04	57,33
2009	33,74	33,74	33,74	35,55	35,55	35,53
2008	39,15	39,15	39,15	51,17	51,17	49,81
2007	25,74	25,74	25,74	29,59	29,59	29,43
2006	49,23	49,23	49,23	48,97	48,97	48,98
	Oslo	Kr.sand	Bergen	Molde	Tr.heim	Tromsø

Figure 5 Energy price Norway[15].

5. LIMENET-DAC Co-benefit against ocean acidification

According to Sustainable Development Goals, HYROGAS wants to implement LIMENET technology not just for removing and sequestrate CO_2 (SDG 13) but it has taken a big R&D effort to increase its efficacy on CO_2 sequestration and storage in a sustainable way through the Ocean. Thanks to HYROGAS members' strong collaboration with the project DESARC MARESANUS[16], a research program between different teams of Politecnico di Milano, University of Pisa and HYROGAS was carry out with the goal to reduce ocean acidification (SDG 14.3). In particular, this is done with LIMENET with addition of "equilibrated-alkalinity[17]" into the sea. Alkalinity increases the buffering effect and decreases pH variations of seawater due to the intake of atmospheric CO_2. Reducing seawater acidification related to the increase of atmospheric CO_2, would ameliorate the resilience of the ocean acidification[18,19].

<1500 words

[15] https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/NO/Daily1/?dd=NO4&view=table

[16] https://www.desarc-maresanus.net/

[17] Hartmann et al. (in review, 2022): Stability of alkalinity in Ocean Alkalinity Enhancement (OAE) approaches – consequences for durability of CO2 storage. https://doi.org/10.5194/bg-2022-126.

b. What is the current technology readiness level (TRL)? Please include performance and stability data that you've already generated (including at what scale) to substantiate the status of your tech.

<500 words

LIMENET – DAC facility can be divided into five parts (See paragraph 2. Technology).

1) **Storage** of the CO_2*, TRL6.*

At the beginning of 2022 a LIMENET TRL6 plant has been installed at La Spezia CSSN port. Tests were performed to evaluate the continuous buffering of CO_2 with $CaCO_3$ (PCC) and $Ca(OH)_2$ forming $Ca(HCO_3)_2$. It is still ongoing a study on the stability of calcium bicarbonates (See paragraph 2. Durability).

[18] https://www.oceannets.eu/ocean-alkalinization/

[19] https://eos.org/editors-vox/understanding-alkalinity-to-quantify-ocean-buffering

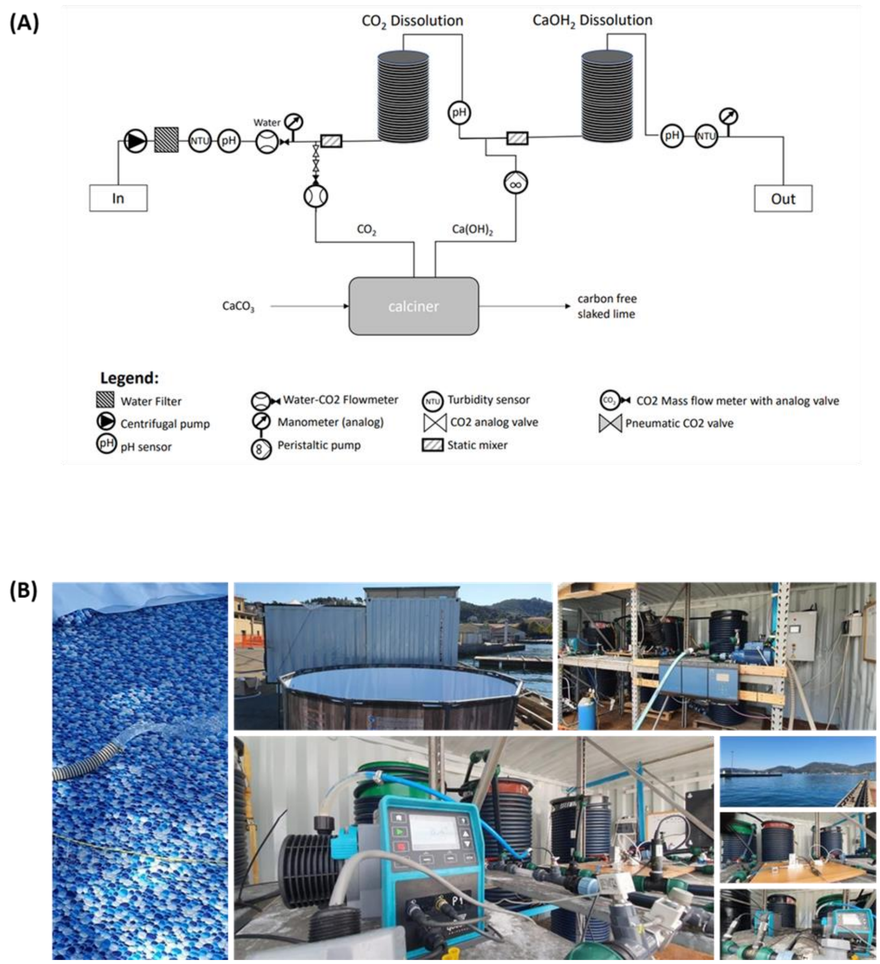

Figure 6 (A) Process flow diagram and (B) visuals of the open-loop BAWL reactor – La Spezia port, Italy, and visuals.

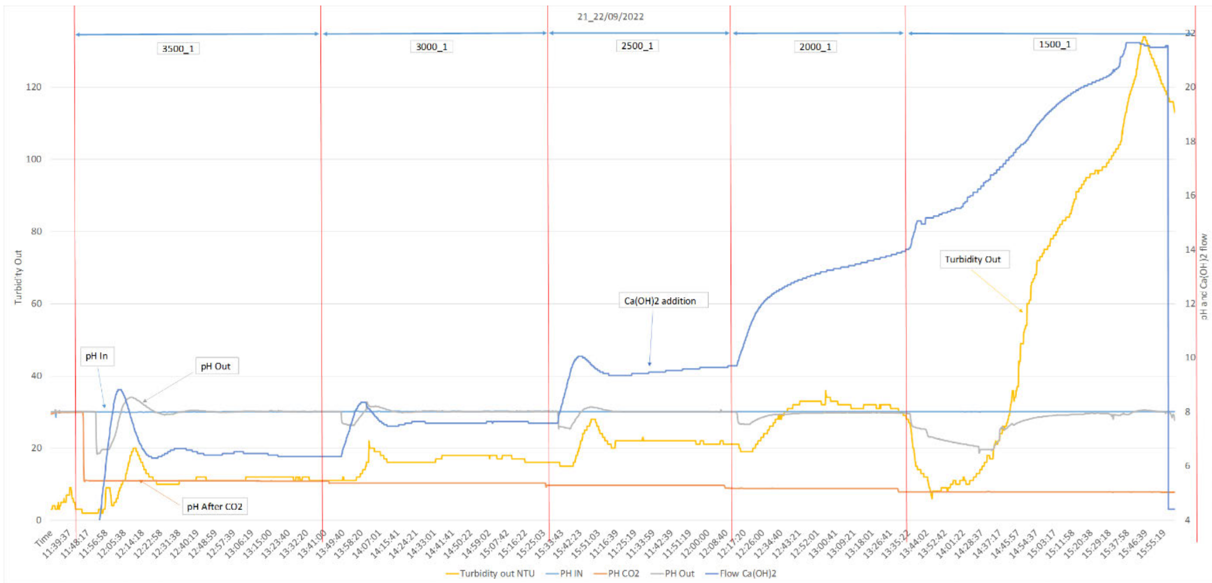

Figure 7 LIMENET circuit with different water-CO_2 ratios.

As shown in Figure 7, it is possible to buffer the CO_2 injected into the seawater stream with $Ca(OH)_2$ and to discharge a water stream with the same pH of the seawater avoiding any $CaCO_3$ precipitation. The absence of $CaCO_3$ precipitation is measured by the low turbidity of the discharged water and, indirectly, by the amount of $Ca(OH)_2$ pumped into the stream of acidic seawater to buffer the CO_2. For the very hot seawater (i.e. >25°C) at La Spezia port, the optimal ratio seawater: CO_2 is above 3000:1. With lower ratios than 2500:1 the system is not stable leading to abiotic $CaCO_3$ precipitation within the LIMENET plant.

Preliminary tests show that it is possible to dissolve $CaCO_3$ (PCC) and $CaCO_3$ (GCC) in a seawater acidic stream in several minutes buffering the CO_2 injected into the seawater stream.

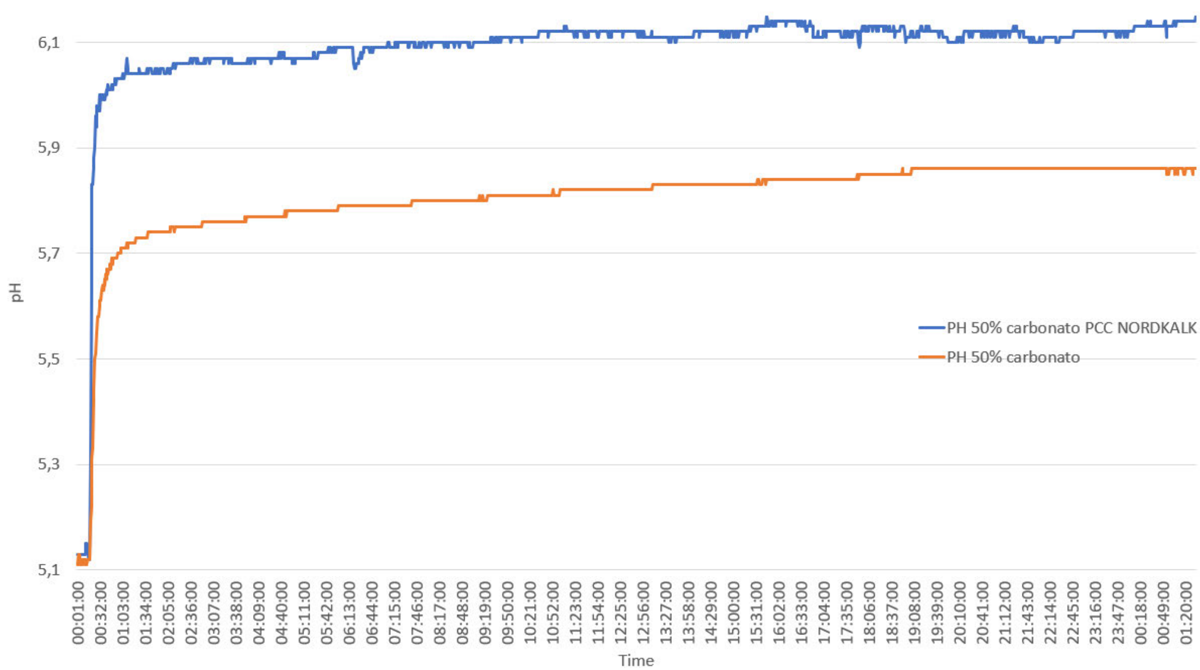

Figure 8 Dissolution test of PCC and GCC in acidic seawater stream

2) **Production** of $Ca(OH)_2$, *TRL9*

The production of CaO with electric calciners is a well-known TRL9 technology.

Figure 9 LIMENET TRL9 electric calciner and slaker in assembling.

3) **Capture** of CO_2, *TRL8 +*

The DAC air contactor is a well-studied and established technology that can be considered TRL8/TRL9 (I.e. Carbon Engineering[20]).

4) **Regeneration** of the K_2CO_3, TRL9

The regeneration of the KOH (or NaOH) with $Ca(OH)_2$ is a well-established technology extensively used in the Kraft process to regenerate the "white liquor" and the separation of the resulting precipitated calcium carbonate (PCC) through decanter centrifuges is a very well-known industrial process[20].

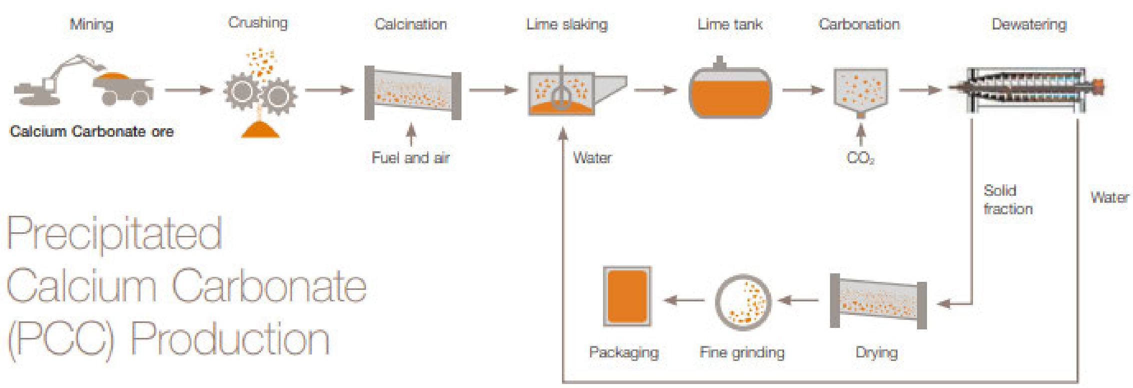

Figure 10 Industrial flow diagram for PCC production from Alfa Laval[21].

5) **Dilution, TRL9**

The dilution of a liquid stream into a water body (wastewater, bine, etc.) is a very well-studied problem and there are many models and technical solutions to optimize the mixing of the discharged water with the surrounding waters within a plume[21].

Considerations:

The overall LIMENET process installed at La Spezia port can be considered TRL6.

The LIMENET–DAC process should be considered with lower TRL than 6 because HYROGAS has not yet tested the air contactor and the regeneration of the KOH. However, since all the other components of the LIMENET-DAC process except the CO_2 storage have high TRL, HYROGAS considers the actual

[20] https://doi.org/10.1016/j.joule.2018.05.006

[20] pep00245en-classification-and-dewatering-of-non-metallic-minerals.pdf (alfalaval.com)

[21] https://www.alfalaval.com/

[21] Dilution Models for Effluent Discharges - Visual Plumes (4th Edition) | US EPA

LIMENET–DAC process as TRL 6.

c. What are the key performance parameters that differentiate your technology (e.g. energy intensity, reaction kinetics, cycle time, volume per X, quality of Y output)? What is your current measured value and what value are you assuming in your nth-of-a-kind (NOAK) TEA?

Key performance parameter	**Current observed value (units)**	**Value assumed in NOAK TEA (units)**	**Why is it feasible to reach the NOAK value?**
storing of CO_2 as calcium bicarbonate	100% No abiotic precipitation No CO_2 degassing	100% No abiotic precipitation No CO_2 degassing	The chemistry is the same for the TRL 6 and NOAK plants
Cost for MWh	Not Applicable	20 ($/MWh)	Due to right location with low LCOE[22].
Energy consumption for ton or stored CO_2	Not applicable	2,6 MWh	Due to the right location with cold seawaters (better Ca solubility) and low ambient temperature (less evaporation losses) that lower the energy requirements

d. Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

HYROGAS' principals[23] are four very experienced professionals with long activity in engineering, managing large projects, consultancy, government charges and academics. Their key field of their activity is energy, especially gasification of biomass and RDF and, for this reason, HYROGAS is involved as EPC and technology provider for the manufacturing, installation, and commissioning of big scale biomass gasification plants for H_2 production.

The experience in high temperature equipment, piping, instrumentation, and control of complex processes is very useful for designing, manufacturing, and managing the LIMENET process.

The key HYROGAS person for this project is Giovanni Cappello, senior engineer with an MBA that is also, among others, the inventor and the promoter of proposed LIMENET technology. He has been involved in different R&D activities on CDR and CCS technologies, ocean liming as well in techno-

[22] Satymov et al. Global-local analysis of cost-optimal onshore wind turbine configurations considering wind classes and hub heights. https://doi.org/10.1016/j.energy.2022.124629

[23] Team — Hyrogas - carbon free hydrogen

economic analysis and environmental impact assessments and have, in particular, already collaborated in the previous research works with DESARC MARESANUS[24].

Beside the senior engineers, HYROGAS can rely on a senior Biologist with a long career in supervising European funded project in Latvia for the Latvian government and that is responsible of its organization, administration and permitting.

In the last months, new junior engineers joined HYROGAS and, in particular, Stefano Cappello that is fully operational on the TRL6 LIMENET pilot plant at La Spezia.

HYROGAS has an advisory board[25] formed by Dennis Meadows and Helga Kromp-Kolb, as scientific consultants, the team of the DESARC MARESANUS project.

Three young pHDs and four engineers from Politecnico di Milano are already collaborating for LIMENET project and are ready to join the HYROGAS team when the deployment of the LIMENET technology will start.

<300 words

e. Are there other organizations you're partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	**Role in the Project**	**Level of Commitment**
Politecnico of Milano	Supporting the scientific studies Supporting the engineering	High level of commitment in R&D. Chemistry, LCA and fluid dynamics expert will help HYROGAS for TRL 7, TRL 8 and TRL 9 implementation
NIVA Norway	Supporting in studying the local impact on biota of alkalinity addition with mesocosm.	Collaborator for Norwegian Grant (see ***Confidential Addendum***) and for LIMENET environmental future study
GEOMAR institute	Supporting in studying the local impact on biota of alkalinity addition with mesocosm.	Strategical potential collaboration for Environmental study of LIMENET
Egenia	Making calcium bicarbonate recognition as permanent storage	Future partner for European regulatory compliance of calcium bicarbonate as permanent storage option
Carbon Engineering	Supplying the best in class air-	No commitment at the moment

[24] DEcreasing Seawater Acidification Removing atmospheric Carbon, Contrastare acidificazione acque, rimuovere co2 (desarc-maresanus.net)

[25] Advisory Board — Hyrogas - carbon free hydrogen

	liquid contactors for DAC	No contacts so far between HYROGAS and Carbon Engineering
Alfa Laval	Supplying the best in class centrifuges	No commitment at the moment No contacts so far between HYROGAS and Alfa Laval

f. What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

<30 words

HYROGAS is expecting, according to TEA calculation, to have the following Gantt diagram if purchases of CO_2 will be warrantied:

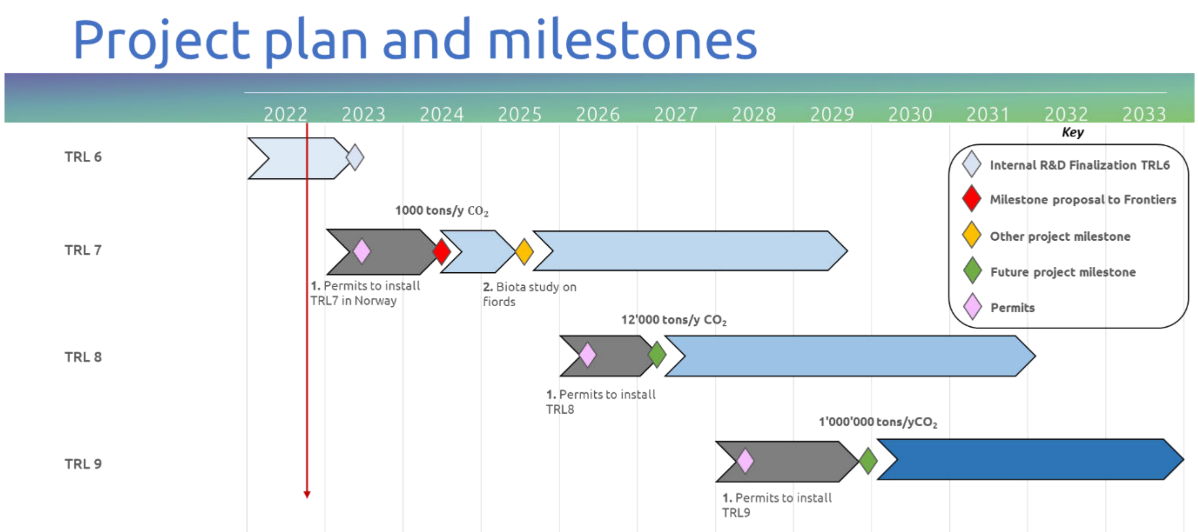

Figure 11 LIMENET milestones.

g. When will CDR occur (start and end dates)? If CDR does not occur uniformly over that time period, describe the distribution of CDR over time. Please include the academic publications, field trial data, or other materials you use to substantiate this distribution.

<100 words

LIMENET-DAC has the capability to remove and store CO_2 from the beginning of its operation. As soon as LIMENET–DAC facility will be completed it will remove CO_2 from air with no seasonal dependency.

HYROGAS prepurchase proposal program consists of different steps:

1) Internal R&D finalization TRL6 (See Figure 11)
2) Remove 1000 gross ton/year of CO_2 from the first TRL7 plant. From Q2 2024 till Q2 2029.
3) Propose to Frontiers, to evaluate HYROGAS TRL8 industrial LIMENET – DAC plant.
4) Remove 12000 gross/year ton of CO_2 from the first TRL8 industrial plant. From Q1 2027 till Q1 2032.

h. Please estimate your gross CDR capacity over the coming years (your total capacity, not just for this proposal).

Year	Estimated gross CDR capacity (tonnes)
2023	0.1
2024	500
2025	1000
2026	1000
2027	1000 + 9000
2028	1000 + 12000
2029	500 + 12000
2030	12000 + 500000
2031	12000 + 1000000

i. List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	Target completion date (eg Q4 2024)
1	Renting or buying area for project	Q1 2023
2	Obtaining environmental and operation permits	Q2[26] 2023
3	Begin to capture and store of 1000 ton/y of CO_2 according to TEA TRL7	Q3 2024

[26] Depending on permits approval

j. What is your IP strategy? Please link to relevant patents, pending or granted, that are available publicly (if applicable).

LIMENET IP is based on three different patents:

1) PLANT AND METHOD FOR PRODUCING DECARBONIZED OXIDE OR HIDROXIDE USING CARBONATE AND ELECTRIC POWER. Patent pending WO 2022/137038 A1[27]
2) APPARATUS AND METHOD FOR ACCELERATED DISSOLUTION OF CARBONATES WITH BUFFERED PH. Patent pending WO 2022/175885 A1[28]
3) PLANT AND METHOD TO IMPROVE THE EFFICIENCY OF THE CAPTURE AND STORAGE OF CO2 USING PRECIPITED CALCIUM CARBONATE. Italian Patent pending: 102022000016347

The IP strategy is to register the patents only into the key potential markets for LIMENET (with low LCOE and available coastline to install plants), to keep the patents within HYROGAS until TRL 7 is completed and then to incorporate a dedicated company SPV open to strategic and financial shareholders to promote the deployment of the technology.

The new SPV will directly develop the new projects selling into the market the negative emissions generated.

Licensing the technology will be evaluated.

<200 words

k. How are you going to finance this project?

HYROGAS will finance development of LIMENET-DAC technology for pre-purchase phase by its own sources based on credit line available from private investor on the basis of Convertible Loan Agreement. The credit line was already used to finance TRL5 and TRL6 prototype development of LIMENET.

<300 words

l. Do you have other CDR buyers for this project? If so, please describe the anticipated purchase volume and level of commitment (e.g., contract signed, in active discussions, to be approached, etc.).

For this specific project we do not have any other possible buyers.

<200 words

[27] https://worldwide.espacenet.com/patent/search/family/075111671/publication/WO2022137038A1?q=pct%2Fib2021%2F061832#:~:text=1.-,WO2022137038A1,-PLANT%20AND%20METHOD

[28] https://worldwide.espacenet.com/patent/search/family/075660225/publication/WO2022175885A1?q=pct%2Fib2022%2F051464

m. What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

No other revenue streams are considered. <200 words

n. Identify risks for this project and how you will mitigate them. Include technical, project execution, ecosystem, financial, and any other risks.

Risk	**Mitigation Strategy**
Discharging permits	The alkaline solution discharged into the sea from the LIMENET – DAC process complies with the existing environmental regulations. In Italy, the TRL 6 LIMENET plant at La Spezia port, got without any problem the environmental permit. For the TRL7 FOAK that we will install in Norway the regulation is: https://lovdata.no/dokument/LF/forskrift/2021-04-14-1356/KAPITTEL_5#%C2%A75-2 where it is possible to see that there is no limitation in discharging waters with high content of calcium bicarbonates and pH 8.

2. Durability

a. Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

< 300 words, including number/range of durability estimate Storage durability in LIMENET can rely on different studies which analyze the permanence of carbon dioxide in seawater after different treatments (more in ***Confidential Addendum***). Rau and Caldeira[29] applied a geochemical model that asses the permanence of CO_2 in seawater as bicarbonate ions after its direct injection under the sea surface and after its reaction with calcite and seawater (AWL process). They assessed that carbon storage after calcite scrubbing could last more

[29] Caldeira, Ken, and Greg H. Rau. "Accelerating carbonate dissolution to sequester carbon dioxide in the ocean: Geochemical implications." Geophysical Research Letters 27.2 (2000): 225-228.

than tens of thousands of years[30]. However, in LIMENET, the treated solution of seawater, carbon dioxide, calcite/PCC, calcium hydroxide has pH equal of seawater's one, indicating that all the carbon dioxide has reacted.

We can also think about the seawater carbonate cycle. Here, the equilibrium between inorganic carbonate species (HCO_3^-, CO_3^{2-}, CO_2) is strictly linked to pH and alkalinity. Moreover, the carbonic acid in seawater is in equilibrium with the gaseous CO_2 in the atmosphere, according to Henry's law. It can be assessed that carbonic acid will start to degas if the fugacity of the solution is higher than -3.4, which corresponds to a CO_2 concentration of 400ppm in the atmosphere.

From our simulations, the treated solution will have CO_2 fugacity $\leq$ -3.4 when pH equals the initial seawater pH. Theoretically, carbon dioxide degassing will depend only on the atmospheric carbon dioxide concentration and on the superficial seawater exchange with lower sweater depth. Since the lower ocean has a lower concentration of CO_2 than the surface layer and atmospheric carbon dioxide concentration will not decrease in the following centuries, storage can be considered permanent.

b. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

<200 words

No durability, physical and socioeconomic risks concern LIMENET, however a fundamental uncertainty is that marine biota may be impacted if:

- Carbonates have toxic trace impurities. With high-quality raw material this is avoided → Strict quality control of carbonate purity!
- Discharging too high-alkaline solution. Gim and others[31] investigate this potential effect and indicate several LC50 for DIC concentration referred to different marine organisms. The stricter LC50 is 11mM for freshwater zooplankton Ceriodaphnia dubia; this value may be exceeded only for LIMENET non diluted solution, and it falls immediately well below the dangerous value after the natural dilution (See Figure 12). No risk is expected for a few seconds above the critical threshold of 11mM of DIC.

[30] Rau, Greg H. "CO2 mitigation via capture and chemical conversion in seawater." Environmental Science & Technology 45.3 (2011): 1088-1092.

[31] Gim, Byeong-Mo, et al. "Potential ecotoxicological effects of elevated bicarbonate ion concentrations on marine organisms." Environmental Pollution 241 (2018): 194-199.

		Total alkalinity (DIC)			
2000_1		3000_1		4000_1	
2000	m3 H20	3000	m3 H20	4000	m3 H20
1	ton CO2	1	ton CO2	1	ton CO2
41.00	mg C/L initial	41.00	mg C/L initial	41.00	mg C/L initial
136.36	mg C/L addition with LIMENET	90.91	mg C/L addition with LIMENET	68.18	mg C/L addition with LIMENET
177.36	mg C/L tot	131.91	mg C/L tot	109.18	mg C/L tot
14.78	mmol C/L tot	10.99	mmol C/L tot	9.10	mmol C/L tot
		LIMENET Dilution			
109.18	mg C/L tot 1a1	86.45	mg C/L tot 1a1	75.09	mg C/L tot 1a1
9.10	mmol C/L tot	7.20	mmol C/L tot	6.26	mmol C/L tot
00:00:07	Time to reach 1:1 diluition	00:00:07	Time to reach 1:1 diluition	00:00:07	Time to reach 1:1 diluition
58.74	mg C/L tot 1a10	54.19	mg C/L tot 1a10	51.92	mg C/L tot 1a10
4.89	mmol C/L tot	4.52	mmol C/L tot	4.33	mmol C/L tot
00:05:43	Time to reach 1:10 diluition	00:05:43	Time to reach 1:10 diluition	00:05:43	Time to reach 1:10 diluition
47.49	mg C/L tot 1a20	45.33	mg C/L tot 1a20	44.25	mg C/L tot 1a20
3.96	mmol C/L tot	3.78	mmol C/L tot	3.69	mmol C/L tot
00:21:35	Time to reach 1:20 diluition	00:21:35	Time to reach 1:20 diluition	00:21:35	Time to reach 1:20 diluition
3.42	mmol C/L fresh sea water				

Figure 12 DIC mM reduction on plume.

To simulate the plume and so dilution speeds we did a MATLAB routine (See Figure 13), with initial conditions:

- water discharging speed: 1 m/s,
- discharging pipe diameter: 1 meter
- no sea currents.

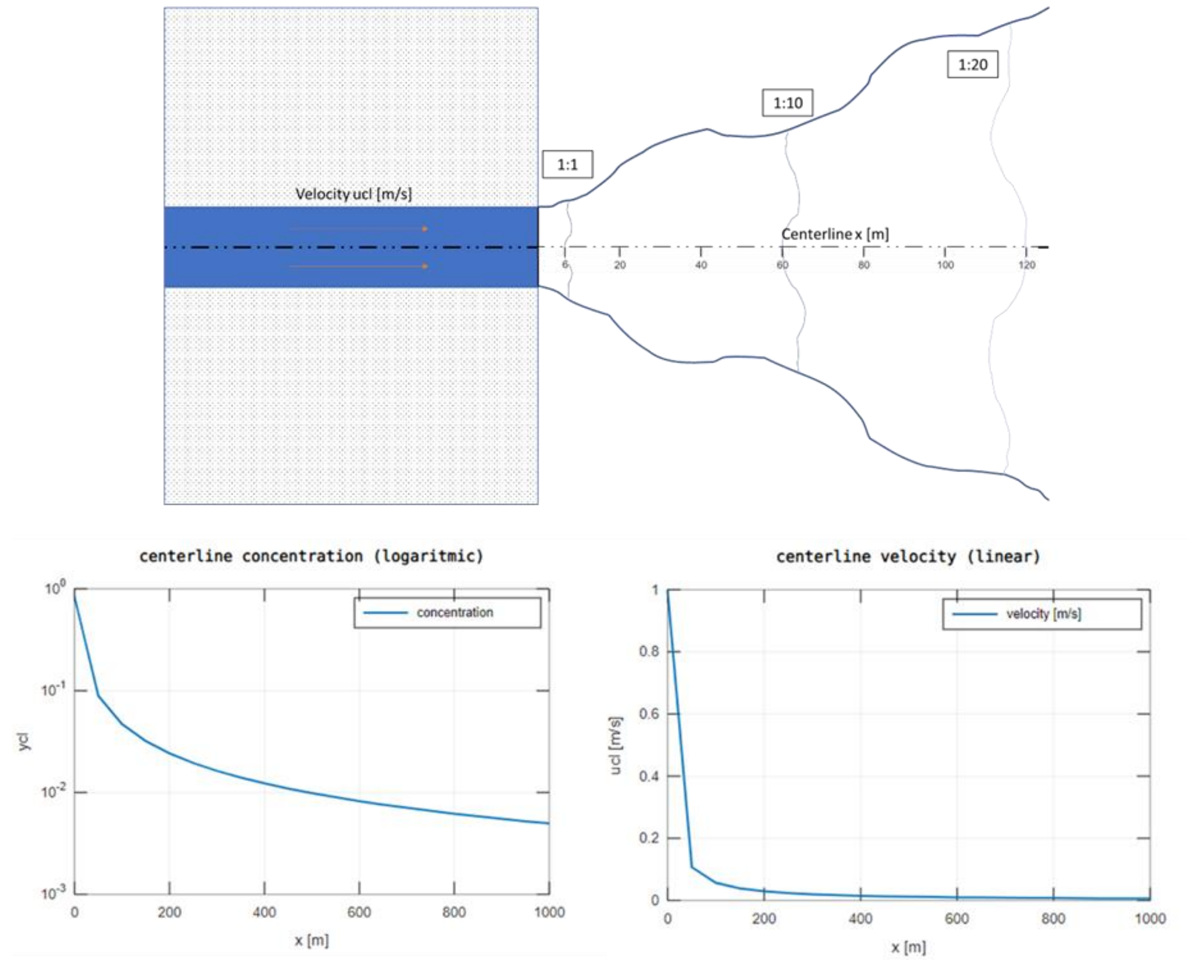

Figure 13 LIMENET discharging plume simulation.

If sea currents or other turbulence will be considered, the dilution will require less time.

3. Gross Removal & Life Cycle Analysis (LCA)

a. How much GROSS CDR will occur over this project's timeline? All tonnage should be described in **metric tonnes** of CO_2 here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	5000 ton
Describe how you calculated that value	This project is based on 0.120 ton/h of captured and stored CO_2 for

	8300 h/y and for 5 years of effective operation. This project has an installed electrical capacity of 260 kw and a limestone consumption of 0.235 ton/h. For more details see mass and energy balance and TEA. Uncertainties are on biotic precipitation. See paragraph 4.c.

b. How many tonnes of CO_2 have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

Capture: approx. 0.05 ton with liming and carbonatation. Stored: approx. 0.1 ton in calcium bicarbonate

c. If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO_2 utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do <u>not</u> include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

For LIMENET-DAC there are no additional avoided emissions.

d. How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

Gross project emissions over the project timeline *(should correspond to the boundary conditions described below this table)*	5000 ton
Emissions / removal ratio *(gross project emissions / gross CDR–must be less than one for net-negative CDR systems)*	0.9042
Net CDR over the project timeline *(gross CDR – gross project emissions)*	4521 ton

e. Provide a process flow diagram (PFD) for your CDR solution, visualizing the project emissions numbers above. This diagram provides the basis for your life cycle analysis (LCA). Some notes:

- The LCA scope should be cradle-to-grave
- For each step in the PFD, include all Scope 1-3 greenhouse gas emissions on a CO_2 equivalent basis
- Do not include CDR claimed by another entity (no double counting)
- For assistance, please:
    - Review the diagram below from the CDR Primer, Charm's application from 2020 for a simple example, or CarbonCure's for a more complex example
    - See University of Michigan's Global CO_2 Initiative resource guide
- If you've had a third-party LCA performed, please link to it. (See ***Confidential Addendum***)

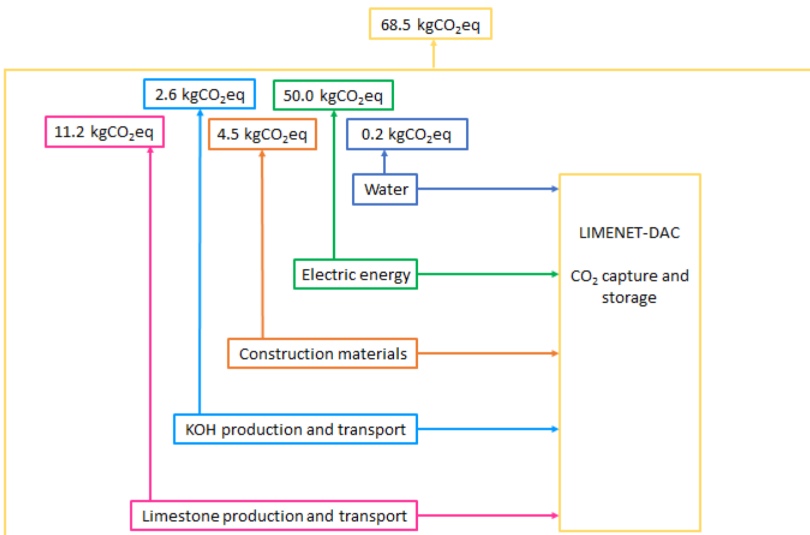

Figure 14 PFD LIMENET – DAC TRL9

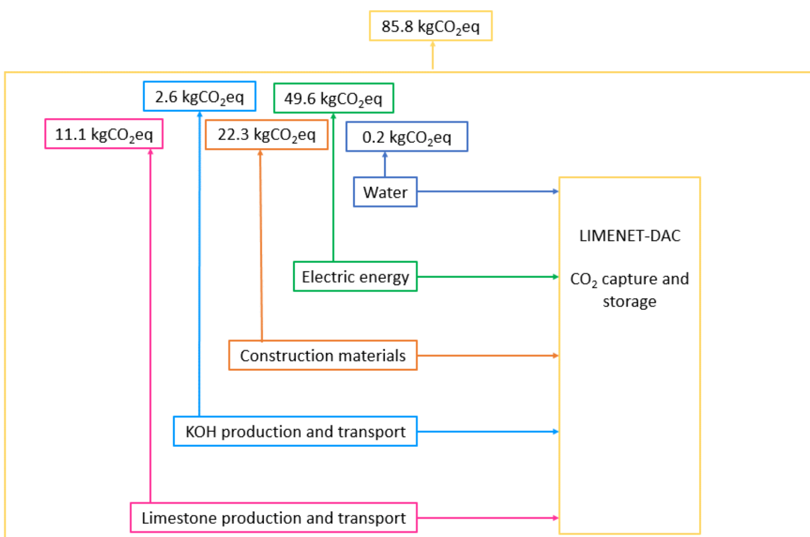

Figure 15 PFD LIMENET – DAC TRL7

f. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

<100 words

The system boundaries include all the process phases, i.e., limestone production and transport, KOH production and transport, water, electric energy and construction materials, which include the production and dismantling of the main components of the process (air contactor, limestone preparation, mill, calciner, slaker, pumps, compressors and pipeline). In order to have more information, please see on ***Confidential Addendum*** where the potential impacts of the process are evaluated through LCA methodology. In addition to Norwegian case, also the results of Italian case are presented and the variation of the process CO_2 removal efficiency due to electricity emission factor is analyzed.

g. Please justify all numbers used to assign emissions to each process step depicted in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. Climeworks' LCA paper.

Process Step	**CO_2(eq) emissions over the project lifetime (metric tonnes)**	**Describe how you calculated that number. Include references where appropriate.**
Limestone production and transport	11.1 kgCO_2eq	From mass balance, limestone production and its transport to the plant assumed 20 km by lorry. (Database Ecoinvent, impact assessment EF method)
KOH production and transport	2.6 kgCO_2eq	From mass balance, due to regeneration efficiency (Database Ecoinvent, impact assessment EF method)
Construction materials	22.3 kgCO_2eq	Construction materials for main components (air contactor, limestone preparation, mill, calciner, slaker, pumps, compressors and pipeline) (Database Ecoinvent, impact assessment EF method)
Electric energy	49.6 kgCO_2eq	From energy balance, assumed from Norway electricity grid (Database Ecoinvent, impact assessment EF method)
Water	0.2 kgCO_2eq	For slaked lime production gfrom mass balance and stoichiometry (Database Ecoinvent, impact assessment

		EF method)
Total	**85.8 kgCO_2eq**	The impacts are calculated starting from impacts of the process at TRL 9 removing 1MtCO_2 for 25 years (more information in ***Confidential Addendum***). Then, the total life cycle GHG emission for construction materials are rescaled for project size proportionally, i.e. 1000 tCO_2 per year working 5 years.

4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

a. Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see Charm's bio-oil sequestration protocol for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage.

HYROGAS is building its own protocol for MRV. Please see ***Confidential Addendum***. <300 words

b. How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

Taking account previous study on calcium bicarbonate stability, the discharging into the sea of the ionic solution from the LIMENET plant at the same pH of the surrounding seawater allows the "almost permanent" storage of all the CO_2[32]. Moreover, the very supersaturated ionic solution formed after the injection of the $Ca(OH)_2$ for buffering the CO_2 should be thoroughly mixed with the surrounding seawater, lowering the overall saturation state of calcite/aragonite (i.e. to $\Omega_{ar} = 5$) and avoiding the risk of $CaCO_3$ precipitation[33]. To guarantee the correct discharging pH, we will monitor the discharging alkaline solution with different process parameters sensor (See Figure 7).

[32] https://carbonplan.org/research/cdr-verification/ocean-alkalinity-enhancement-mineral

[33] Moras et al. (2021) Ocean Alkalinity Enhancement - Avoiding runaway CaCO3 precipitation during quick and hydrated lime dissolution - https://doi.org/10.5194/bg-2021-330

To guarantee that the discharged waters will be properly mixed with the surrounding seawaters, for every discharge point a computational simulation of the plume will be performed taking in consideration the local morphology of the seabed and sea conditions (i.e., currents and tides). <200 words

c. This tool diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:

- In the first column, list the quantification components from the Quantification Tool relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
- In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
- See this post for details on Frontier's MRV approach and a sample uncertainty discount calculation and this Supplier Measurement & Verification Q&A document for additional guidance.

Quantification component Include each component from the Quantification Tool relevant to your project	**Discuss the uncertainty impact related to your project** Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
Mineral dissolution	In LIMENET TRL6, experimental results show a buffering efficiency of 100% of the CO_2 injected into the seawater stream with $Ca(OH)_2$ because it is possible to discharge the ionic solution at the same pH of the surrounding seawater without any degassing (i.e. CO_2 fugacity ≤ -3.4) or $CaCO_3$ precipitation.
Abiotic precipitation	Numerical simulations of the dilution factor in plumes at the discharge point show that the Ω_{ar} of the discharged alkaline solution reaches a value below 5 in few seconds/minutes. This allows, according to literature and experimental results on stability of bicarbonates, to avoid any abiotic $CaCO_3$

	precipitation.
Biotic calcification response	Because LIMENET discharges an alkaline solution into the sea we assume that, if local biota (near the discharge point) uses LIMENET alkalinity, there is a decrease in the CO_2 removal efficiency. The local biotic calcification response can be very different in closed gulfs (i.e. fiords) where the discharged alkalinity can accumulate[26] from open and deep waters where currents and tides pay a very important role in mixing the discharged alkalinity. The biotic calcification response on increasing alkalinity of the overall ocean is not a problem for the first LIMENET-DAC plants (i.e. up to several Gton/y CO_2 captured and stored) due to the extreme dilutions of the discharged alkalinity and the overlapping with the effects on biota of the ongoing ocean acidification[27]. This topic overreaches the knowledge, the scope, and the capabilities of HYROGAS and should be assessed by the scientific community.
Secondary precipitation of $CaCO_3$	Numerical simulations of the dilution factor in plumes at the discharge point show that the Ω_{ar} of the discharged alkaline solution reaches a value below 5 in a few seconds/minutes. This allows, according to literature and experimental results on stability of bicarbonates, to avoid any secondary $CaCO_3$ precipitation.

d. Based on your responses to 4I, what percentage of the net CDR do you think should be discounted for each of these factors above and in aggregate to appropriately reflect these uncertainties?

For biotic calcification, in a very conservative way, we can estimate 1%. Subtracted to LCA results. <50 words

e. Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

One uncertainty that this project wants to reduce is the response of calcifying organisms on alkalinity addition into seawaters and quantifying its effect at any single LIMENET discharge point. This will be done with our partner in Environmental R&D with a specific study of different alkalinity on different

[26] Kirchner et al. (2020): Carbon capture via accelerated weathering of limestone: Modeling local impacts on the carbonate chemistry of the southern North Sea. doi.org/10.1016/j.ijggc.2019.102855 Received 16 January 2019; Received in revised

[27] Ferderer et al. (2022): Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community. doi.org/10.5194/bg-2022-17

biota in mesocosms, through plume modelling that takes into consideration the local conditions and through direct submarine observations.
<200 words

f. Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn't yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

a. What is the levelized price per net metric tonne of CO_2 removed for the project you're proposing Frontier purchase from? This does not need to exactly match the cost calculated for "This Project" in the TEA spreadsheet (e.g., it's expected to include a margin), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

1996 $/ton CO_2 according to TRL7 in the TEA spread sheet

b. Please break out the components of this levelized price per metric tonne.

Component	**Levelized price of net CDR for this project ($/tonne)**
Capex	958
Opex (excluding measurement)	899
Quantification of net removal (field measurements, modeling, university study etc.)[34]	109

[34] This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

Third party verification and registry fees (if applicable)	30
Total	1996 (should match 5(a))

c. Describe the parameters that have the greatest sensitivity to cost (e.g., manufacturing efficiencies, material cost, material lifetime, etc.). For each parameter you identify, tell us what the current value is, and what value you are assuming for your NOAK commercial-scale TEA. If this includes parameters you already identified iI(c), please repeat them here (if applicable). Broadly, what would need to be true for your approach to achieve a cost of $100/tonne?

Parameter with high impact on cost	**Current value (units)**	**Value assumed in NOAK TEA (units)**	**Why is it feasible to reach the NOAK value?**
C electricity	50 $/MWh	20 $/MWh	Right location for low LCOE
C $CaCO_3$	14.5 $/Mton	5 $/ton	Large size quarry
C levelized capex	958 $/ton	48 $/ton	Economy of scale
C levelized opex	233 $/ton	77 $/ton	Economy of scale

d. What aspects of your cost analysis are you least confident in?

> General increase in costs (inflation) and interest rates due to the geopolitical situation.
>
> Our cost analysis is done without considering the possible sharp increase on prices from the suppliers.
>
> <100 words

e. How do the CDR costs calculated in the TEA spreadsheet compare with your own models? If there are large differences, please describe why that might be (e.g., you're assuming different learning rates, different multipliers to get from Bare Erected Cost to Total Overnight Cost, favorable contract terms, etc.).

> <200 words
>
> HYROGAS CDR costs were calculated without taking into consideration the scalability factors but only

the FOAK case. HYROGAS also calculated the CDR costs considering a fix amount of contingencies, not depending on the class of capital and TRL.

f. What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

<50 words

A deeper knowledge on the effects on the ocean of the additional alkalinity and the recognition by the legislation of the main countries (i.e., Europe, USA, Japan, Australia, etc.) that the storage of CO_2 in form of calcium bicarbonates into seawater is a permanent CO_2 storage.

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

a. Who have you identified as relevant external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

<300 words
According to the power-interest grid (See Figure 16), HYROGAS has organized its external stakeholders in three different sections:

1) La Spezia TRL6 prototype
2) LIMENET certifications
3) LIMENET development TRL7

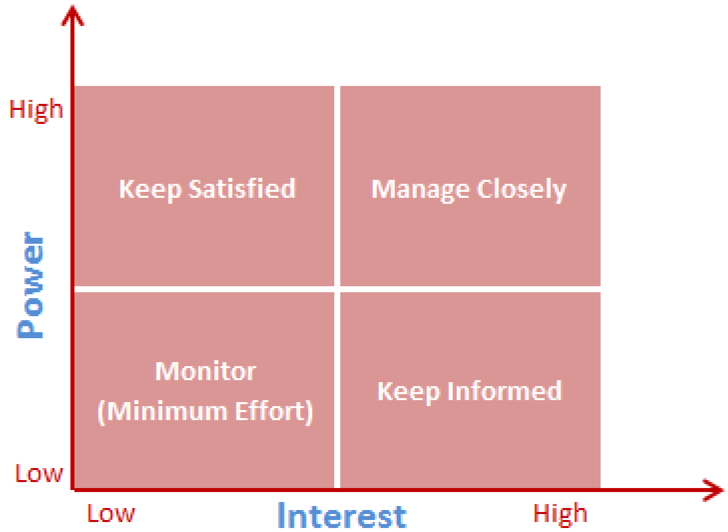

Figure 16 –interest grid Adapted from Mendelow, A.L. (1'81). 'Environmental Scanning - The Impact of the Stakeholder Concept,' ICIS 1981 Proceedings, 20.

Please see ***Confidential Addendum***.

b. If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's community engagement and governance approach as an example and Arnestein's Ladder of Citizen Participation for a framework on community input.*

Few years ago, one of the HYROGAS shareholder members began a collaboration with Politecnico di Milano meeting there many people with the same goal: find a solution to climate change that has a sustainable approach. Among other studies, OAE has been found to be one of the most promising technologies to solve the problem at Gton level. This community of multidisciplinary scientists, professors, students, doctorates, investors, and entrepreneurs founded the DESARC MARESANUS project[35]. The DESARC MARESANUS scientific activity, mainly financed by AMUNDI (Credit Agricole) and EULA (European Lime Association) produced the following scientific works[36]
The LIMENET process and then the LIMENET – DAC process were born within the DESARC MARESANUS project thanks to the intuition of one of its team members. The scientific side of the LIMENET team is formed by most of the participants of the DESARC MARESANUS project while the entrepreneurial side is formed by HYROGAS shareholders that are funding the LIMENET TRL6 at La Spezia port and that will develop and deploy the LIMENET technology.
HYROGAS aims that part of the members of the DESARC MARESANUS project will work actively in the industrial development of the LIMENET – DAC projects.

<300 words

[35] https://www.desarc-maresanus.net/

[36] articoli scientifici deacidificazione (desarc-maresanus.net)

c. If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

LIMENET Team has learned:
- Team working on multidisciplinary aspects
- To face the scientific scrutiny of members of the scientific community
- To have a deep knowledge of the scientific literature
- To write scientific articles
- How to direct communication more effectively through continuous dialogue with team members, student associations, and by participating in scientific conferences.

Modifications are constantly done to our project according to experimental results or new scientific findings.
<100 words

d. Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

The pillars of a medium-term strategy for HYROGAS are:
1) Involvement of trade associations of hard to abate activities (aviation and heavy transport) to sensitize them and propose the service of offset.
2) Elaboration of a communication strategy at national and European/USA level with the collaboration of local/country institutions.
3) Mapping and making contacts with foundations and 3rd sector organizations active on climate change and specifically for OAE.

<100 words

7. Environmental Justice[37]

As a part of Frontier's Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

LIMENET-DAC aims to contribute to SDG 13 (urgent action to combat climate-change and its impacts) thanks to CO_2 capture and storage and toward SDG 14, target 14.3 (minimize and address the impacts

[37] For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's Environmental Justice Reading Materials, AirMiners Environmental and Social Justice Resource Repository, and the Foundation for Climate Restoration's Resource Database

of ocean acidification, including through enhanced scientific cooperation at all levels) implementing partnerships with scientific institutions.

Other considerations:

1) LIMENET-DAC is best suited where renewable energy resources are a surplus, (usually where nature manifests harsh condition). This often goes in parallel with small population density as in Northern Norway's case, (location chosen for our very first unit).
2) Constructing plants in low population areas implies that LIMENET-DAC can have a high impact on local communities' life, creating jobs in remote areas and bringing national relevance.
3) Our technology, compared to geological CCS, offers the advantage of capturing and storing the CO_2 locally without the need to transport it and allows us to locate plants strategically close to raw materials.
4) The raw material (i.e. limestone) sourcing and its usage is done locally, in the same place of extraction. No export.
5) CO_2 capture and storage benefits everywhere.
6) The project promotes international and multidisciplinary work bringing together different stakeholders.
7) The project uses 100% renewable energy.

<200 words

b. How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

LIMENET, within the DESARC MARESANUS project, was born as an international cooperation project bringing together people striving for a better world. We think that every connection has enriched us in a unique way that helped us get here.
Our dream is to create an ever-growing inclusive environment where everyone sharing our dream is welcomed and is pushed to give their unique personal contribution to the climate crisis.
LIMENET can also be implemented to reduce emission in hard to abate flue gasses or can also be used to produce carbon free slaked lime for cement industry.
Reducing emission may lead to having a potential revenue stream on regulated markets such as European ETS.
Even if the addition of alkalinity into the oceans is still being studied among different research studies (i.e. GEOMAR, NIVA, University of Pisa) LIMENET is expected to have a positive influence on water quality, especially in a confined environment such as a Norwegian fiords. This may lead to positive impact on local marine biota that could lead to a possible new revenue stream with a collaboration with local fish industries. In fact, increasing seawater alkalinity may benefit fiordal fish farmers' culture[38]. According to recent studies fish industry is beginning to suffer ocean acidification and low alkalinity[39]. Increasing alkalinity also helps reduce pH variation during the day and leniting this arising issue in a core local business.

[38] https://portal.fiskeridir.no/portal/apps/webappviewer/index.html?id=87d862c458774397a8466b148e3dd147

[39] Heinrich, L. & Krause, T. (2016). Fishing in acid waters – a vulnerability assessment of the Norwegian fishing industry in the face of increasing ocean acidification. Integrated Environmental Assessment and Management. https://doi.org/10.1002/ieam.1843

LIMENET moreover wants to use (for the first plants) just existing renewable energy, then, it must be associated to specific renewable bigger energy installations (See Norwegian energy plan[40]).

<300 words

8. Legal and Regulatory Compliance

a. What legal opinions, if any, have you received regarding deployment of your solution?

HYROGAS already received a legal permit for the TRL6 pilot plant installed at La Spezia port from the Italian environmental agency (ARPAL) and the province office of La Spezia to operate and discharge the alkaline waters into the sea. The TRL6 pilot was also approved by the Italian navy environmental department to be installed at CSSN harbor.

<100 words

b. What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

A NOAK LIMENET-DAC plant for capturing and storing 1 Mton/y of CO_2 will require similar permits to any industrial park that insists on a 25-ha area. Possibly the required permits will be more focused on the visual and environmental impact of these plants placed on pristine coastlines than on direct pollution concerns.
The TRL7 and TRL8 LIMENET-DAC plants will be installed in existing port facility/industrial areas with access to existing infrastructure.
It is also mandatory to ask permits for discharging water according the local regulations (i.e., the European directive 91/271/CEE if the plant is installed in Europe).
<100 words

c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

The LIMENET-DAC plants, if installed in EUROPE, are subject to the EU ETS (Emission Trading System) regulation that fix a maximum calcination production limit of 50 ton/day of CaO (i.e., a LIMENET-DAC plant for 12.000 ton/y of CO_2) to avoid being included inside the ETS system. Going above this

[40] https://experience.arcgis.com/experience/a62eaf684ee14b4b8fbd007ea180a2af/page/Ocean-based-Industries/

threshold, the plant should pay the CO_2 emissions generated by the calciner at market price until the storage of the CO_2 in form of calcium bicarbonates into seawater will be recognized by the ETS directive 2066-2018, art 49 paragraph 1 comma b as permanent storage. <100 words

d. In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

There are no uncertainties on the steps to make LIMENET + DAC implemented: 1) Industrial plant construction permits 2) ETS directive 2066-2018, art 49 paragraph 1 comma b for the LIMENET system installed in Europe 3) Environmental permit for discharging treated waters from each plant HYROGAS does not acknowledge other specific requirements. <100 words

e. Do you intend to receive any tax credits during the proposed delivery window for Frontier's purchase? If so, please explain how you will avoid double counting.

HYROGAS intends not to receive any tax credit. <50 words

9. Offer to Frontier

This table constitutes your **offer to Frontier**, and will form the basis of contract discussions if you are selected for purchase.

Proposed CDR over the project lifetime (tonnes) *(should be net volume after taking into account the uncertainty discount proposeIn 4(c))*	4521 ton
Delivery window *(at what point should Frontier consider your contract complete? Should match 1(f))*	Q2 2029
Levelized Price (\$/metric tonne CO_2) *(This is the price per tonne of your offer to us for the tonnage described above)*	1996 \$/tonCO_2

Application Supplement: DAC

(Only fill out this supplement if it applies to you)

Note: these questions are with regards only to air capture: e.g. your air contactors, sorbents or solvents, etc. Separately, there exist Geologic Injection and CO_2 Utilization supplements. We anticipate that most companies filling out this DAC supplement should ALSO fill out one of those supplements to describe their use of the CO_2 stream that's an output of the capture system detailed here.

Physical Footprint

1. What is the physical land footprint of this project, and how do you anticipate this will change over the next few years? This should include your entire physical footprint, i.e., how much land is not available for other use because your project exists. Also, what is the estimated footprint if this approach was removing 100 million tons of CO_2 per year?

Land footprint of this project (km^2)	The footprint of TRL7 project is 0.002 km^2, for TRL9 will be more less 0.25 km^2 (1000000 CO_2ton/year). This is because LIMENET bicarbonates reactors will be placed below DAC facility.
Land footprint of this tech if scaled to 100 million ton of CO_2 removed per year (km^2)	The footprint will be around 15-20 km^2 divided in 10 – 100 different locations

Capture Materials and Processes

1. What material(s) is/are you using to remove CO_2?

<50 words

The consumable materials used to remove CO_2 are:

1) Potassium hydroxide
2) Seawater

The consumable materials used to store CO_2 are:

1) Seawater
2) Limestone

2. How do you source your material(s)? Discuss how this sourcing strategy might change as your solution scales. Note any externalities associated with the sourcing or manufacture of it (e.g., hazardous wastes, mining, etc.). You should have already included the associated carbon intensities in your LCA in Section 3.

<300 words–LIMENET - DAC plant has different major requirements:

- Calcium carbonate
- Potassium carbonate (1 kg per ton of negative CO_2)
- Seawater
- Renewable electricity
- Available coastal areas

For the first years of LIMENET-DAC deployment, HYROGAS will require the support of local suppliers such as local miners or energy providers. Then, when it will scale up, it will be needed a more accurate study on the supply chain and, eventually, to incorporate the quarry activity and the electric energy production to the big scale projects.

Calcium Carbonate represents about 4% of the Earth's crust[41], making it one of the most abundant minerals on Earth. For that reason, in order to scale up LIMENET must have in future dedicated mines (according to Environmental Justice methodology).

Potassium represents 2.6% of surface of the Earth's crust, making it the seventh most abundant mineral on Earth[42]. The ratio of potassium carbonate utilization respect to calcium carbonate in the–LIMENET - DAC process is 2300:1 in weight. According to the European survey on Potash, the world reserves are mostly concentrated in Canada, Russian, Belarus, China[43].

Sea water is simply accessible by installing plants on coastal areas. The key point for scaling the LIMENET-DAC technology is to get cheap renewable electricity and available coastal areas (See–LIMENET - DAC industrial scaling).

3. How much energy is required for your process to remove 1 net tonne of CO_2 right now (in GJ/tonne)? Break that down into thermal and electrical energy, if applicable. What energy intensity are you assuming for your NOAK TEA?

Electric energy: 9.36 GJ/ton

No thermal energy is used

[41] Aït-Kadi, Hébert, Bouzenad 2015

[42] Potassium - Wikipedia

[43] https://rmis.jrc.ec.europa.eu/apps/rmp2/#/Potash

For the NOAK TEA the energy intensity is 9.36 GJ/ton

<100 words

4. What is your proposed source of energy for this project? What is its assumed carbon intensity? How will this change over the duration of your project? (You should have already included the associated carbon intensities in your LCA in Section 3).

LIMENET-DAC aims to use 100% renewable energy. For TRL7 and TRL8 we will use Norwegian electricity grid with its respective carbon footprint of 19 gCO_{2eq}/kWh that is considered for the LCA. The LCA is done with Ecoinvent process (version 3.5), impacts calculated with EF method with energetical mix of IEA.

In LIMENET-DAC LCA, the carbon intensity is:

- 1000 ton/y TRL7 with a 5 years operations: 8.2%
- 1000000 ton/y TRL9 with 25 years operations: 6.8%

<100 words

5. Besides energy, what other resources do you require (if any, such as water)? Where and how are you sourcing these resources, and what happens to them after they pass through your system? (You should have already included the associated carbon intensities in your LCA in Section 3).

<100 words

According to LIMENET-DAC LCA, those sources are used:

Raw material	***Where it goes***	***Where it is taken***
Calcium carbonate	into the sea	taken from local quarry
Potassium hydroxide	into the air as drift loss	supplier
Sea water	into the sea	from the sea

6. Do you have experimental data describing how your system's CDR performance changes over time? If so, please include that data here and specify whether it's based on the number of cycles or calendar life.

<100 words

The buffering reaction has higher efficiency with low sea water temperatures. This means that it is possible to have higher efficiency because of lower pumping requirements. The opposite can happen during the hot season: the Mass&Energy balance presented in this document is done considering hot water temperature, thus a conservative evaluation if the LIMENET plants will be installed in cold climate areas. To prevent fouling of the pipe system, electrolytic antifouling protection will be installed. There is no foreseen performance decay over time.

7. What happens to your capture medium at end-of-life? Please note if it is hazardous or requires some special disposal, and how you ensure end-of-life safety.

<100 words

LIMENET - DAC does not have a specific medium except a solution of potassium hydroxide and potassium carbonate. There is no end to life of such a solution and no disposal is needed. If a forced disposal of such a solution is needed, it can be used as potash fertilizer in agriculture.

8. Several direct air technologies are currently being deployed around the world. Why does your DAC technology have a better chance to scale and reach low cost than the state of the art?

<200 words

LIMENET features make it optimal to match with available alkaline liquid DAC technologies.

The key advantage of LIMENET-DAC technology is its modularity that will allow deployment scheduling, full industrialization and working on a rolling basis with significant economies of scale, low risk and financial optimization.

The same DAC technology coupled with a geological CCS is limited by long development times[44] (i.e. from 5 to 10 years for each tailor-made project), large projects to lower specific costs[45], limitation to specific areas where the geological storage is possible (i.e. with suitable caprock or with water availability for CWI) or by the obligation to transport the CO_2 to available geological storage sites[46].

[44] Ma et al. (2022); Carbon Capture and Storage: History and the Road Ahead. doi.org/10.1016/j.eng.2021.11.024

[45] Gassnova (2020): Potential for reduced costs for carbon capture, transport and storage value chains (CCS)

[46] Northern Lights (norlights.com)

The key difference between LIMENET and other geological storages is that the CO_2 is fixed into bicarbonates in few minutes and permanently stored while the mineralization of the CO_2 injected underground will need, in the best case, a couple of years[47].

[47] IEAGHG (2017): Review of CO2 storage in basalt. IEAGHG Document Manager

Application Supplement: Ocean

(Only fill out this supplement if it applies to you)

Physical Footprint

1. Describe the geography of your deployment, its relationship to coastlines, shipping channels, other human or animal activity, etc.

<200 words

LIMENET-DAC must be developed close to the coastline (not necessarily on the shore) in places with low LCOE. Plants must have an uptake point and discharging point for seawater far enough that the uptake does not take discharge waters: this could be done using submarine discharge/feeding pipes (i.e. HDPE pipes) of few km length perpendicular to the coastline or a tunnel/canal connecting two sides of a peninsula[48] (i.e. 8m diameter tunnel is needed for 1Mton/y) feeding the LIMENET-DAC plant from the back (no need of discharge pipes see ***Confidential Addendum***).

The 1 Mton/y plants could be located on the coast singularly or in clusters of few plants to have a sufficient number of workers to install a town with all the services. The plants should be installed at a reasonable distance one from the other (i.e. 20 km). With this spacing and clusters of 10 Mton, only in the Argentinean Patagonia (1500km) it is possible to install 750 Mton/y of LIMENET-DAC.

Worldwide there are approx. 30.000 km of coasts with similar characteristics: the deployment of LIMENET-DAC should start from the easiest places with the lowest LCOE, with the highest social benefits and the lowest environmental impact.

2. Please describe your physical footprint in detail. Consider surface area, depth, expected interaction with ocean currents and upwelling/downwelling processes, etc.
    a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

<200 words
Please see ***Confidential Addendum***

3. Imagine, hypothetically, that you've scaled up and are sequestering 100Mt of CO_2/yr. Please project your footprint at that scale, considering the same attributes you did above (we recognize this has significant uncertainty, feel free to provide ranges and a brief description).

[48] English - Stad skipstunnel

a. If you've also filled out the Biomass supplement and fully articulated these details there, simply write N/A.

<200 words

For 100 Mton/y of CO_2 it is possible to install 10 different clusters of 10Mton each at 20 km (it is a value to be assessed with a deep environmental study) distance from the nearest one.

The total footprint will be 250 – 300 ha, also considering the access roads.

If the project is executed in the Argentinean Patagonia or on the Falkland Islands where the LCOE of the onshore wind is very interesting, there is available space to install wind mills, the land needed for each cluster will not be a limiting factor.

A cluster of 10Mton/y of CO_2 will employ at least 300 direct workers (without considering the eventual workers for the limestone quarry, transport, maintenance to the windmills and services) that justify the creation of a new town nearby.

Potential to Scale

4. Building large systems on or in the ocean is hard. What are your core engineering challenges and constraints (not covered already within 1(n)? Is there any historical precedent for the work you propose?

<200 words

The LIMENET-DAC plants will be located in harsh environments but on land where is possible to use traditional technologies for their erection.

The only difficulty could arise from the installation of the large bore HDPE pipelines on the seabed in harsh waters in those location where the coastline is straight (i.e. Argentinean Patagonia), without the possibility to dig tunnels from different part of a peninsula/island (i.e. Chilean Patagonia).

Digging short tunnels/canals (from 1 to 4 km) could be a technically available, long lasting, and cheaper solution than installing underwater HDPE pipes in places where the orography is favorable even if installing large diameter submarine HDPE pipes is a well-known technology[49].

Externalities and Ecosystem Impacts

5. What are potential negative impacts of your approach on ocean ecosystems?

<200 words

[49] Pro_grossrohr_en-WEBSC.pdf (agru.at)

According to J.S. Khim et al.[50], it is important not to discharge too high alkalinity waters into the sea because some biota would suffer through time. LIMENET is always discharging alkalinity below this threshold that J.S. Khim et al. found as 11 mmol/DIC. At the discharge point alkalinity from the LIMENET - DAC process is around 10 mmol/DIC. According to our preliminary plume simulation model, after few minutes, with the dilution of the alkaline solution in the plume, alkalinity drops to 4 mmol/DIC (See Figure 12 DIC mM reduction on plume.). This value is largely below the critical threshold for generating negative impacts to the ocean ecosystem (See Figure 12).

Deeper studies must be conducted to see which would be the best alkalinity concentration in the discharged waters for better biota welfare.

6. How will you mitigate the potential for negative ecosystem impacts (e.g., eutrophication and alkalinity/pH)? How will you quantify and monitor the impact of your solution on ocean ecosystems and organisms?

If, after the scientific studies on the biota response, we discover that is better to have more dilution at the discharge point, it is very simple to adjust the LIMENET process to these new values: the only drawback would be the increased pumping energy requirements and a higher specific CAPEX cost.

A continuous monitoring of seawater indexes near the discharge point will be carried out by process sensors and third-party companies will ensure the compliance of each plant to the agreed MRV.

A specific HAZOP analysis will be done to avoid any kind of environmental risks for each plant. Then HYROGAS will adequate its process to specific ISO 14001-2015.

HYROGAS is developing with NIVA a protocol to monitor seawater water chemical properties near the LIMENET discharge point.

As a corollary, continuous improvement of environmental justice will be performed as an internal company pillar to uninterruptedly research for best ratio between land used/raw material uses on CO_2 stored.

<200 words

[50] J.S. Khim et al. Potential ecotoxicological effects of elevated bicarbonate ion concentrations on marine organisms. https://doi.org/10.1016/j.envpol.2018.05.057