puro·earth

Public Project Description

This document is a project description, made available in the Puro Registry, to summarize the information available about a certified production facility.

This project description corresponds to the following **Production Facility** and the **CO_2 Removal supplier** as its registrant:

Production Facility	
Facility Name	Orca Plant
Location	Orca Plant, Nordurvellir 4, 816 Ölfus
Facility ID	631817
Facility GSRN	643002406801001425
Host Country	Iceland
Methodology	Geologically Stored Carbon
Crediting Period, start date	2023-Dec-01
Crediting Period, end date	2028-Nov-30
This table is filled-in by Puro Registry	

Registrant	
CO_2 Removal Supplier name	Climeworks AG
Business ID	CHE-115234406
Address	Birchstrasse 155, 8050 Zurich, Switzerland
KYC passed	yes
Has this facility been registered in another registry / Period	No / None
This table is filled-in by Puro Registry	

The above-mentioned production facility has undergone the following audit, during which the project description, alongside other audit documents were verified.

Facility Audit information	
Production Facility Audit	Combined Facility and Output Audit
Methodology name	Geologically stored carbon
Methodology version	Edition 2021 v1.1
General Rules version	3.1
Crediting Period, start date	2023-Dec-01
Crediting Period, end date	2028-Nov-30
Audit Body	DNV
Audit conclusion	Production facility has demonstrated conformity to Puro Standard and Methodology requirements
This table is filled-in by Puro Registry.	

Contents

1. Overview of activity, its location, and operators

The information in this section provides an overview of how and where carbon dioxide removal is achieved, and by whom.

1.1. Non-technical description

Instructions	*Please provide a non-technical description of the carbon removal activity taking place at the production facility. Word limit: 100 words.*
Non-technical description	Project Orca is a Direct Air Capture (DAC) and mineral storage project owned by Climeworks and operated by Climeworks and partner Carbfix. Project Orca captures CO_2 from the atmosphere using Climeworks' Direct Air Capture and stores the CO_2 permanently underground using Carbfix's in-situ carbon mineralization in a close by geological storage site in southern Iceland.

1.2. Locations

Instructions	*Please provide a list of locations associated with the carbon removal activity. Add Additional locations as needed for the sourcing of a specific feedstock or use of manufactured materials*
Production Facility Location (as registered)	Address: Hellisheiði Geothermal Power Station, south of Reykjavik (Orca Plant, Nordurvellir 4, 816 Ölfus). Coordinates (WSG84): Project Orca including the DAC facility (64.044, -21.400) and the storage site (64.026, -21.432)
Additional location(s)	*Specify purpose, location, address, coordinates, to the extent possible, for one or multiple additional locations.* Climeworks DAC facility is located at the ON Power Geothermal Park of the Hellisheiði Geothermal Power Station.

1.3. Operators

Instructions	*Please provide a full list of operators or organizations that contribute to the removal activity. Add rows as necessary.*
CO_2 **Removal Supplier**	*Entity name:* Climeworks AG *Entity Business ID:* CHE-115234406 *Entity address:* Birchstrasse 155, Zurich 8050, Switzerland *Role of entity:* **DAC operator**
Organization 2	*Entity name:* Carbfix hf. *Entity registration number:* 531022-0840 *Entity address:* Höfðabakki 9D, 110 Reykjavík, Iceland *Role of entity:* **Transport and Storage operator**
Organization 3	*Entity name:* ON Power. *Entity registration number:* 471119-0830 *Entity address:* Bæjarháls 1, Reykjavik 110, Iceland *Role of entity:* **Power supplier**

….

2. Technical description of the removal activity

The information in this section provides more technical details about the technologies and processes deployed to achieve carbon dioxide removal.

Instructions	*Please provide a technical description of the carbon removal activity taking place at the production facility. Word limit: 500 words.*
Summary of technical description	Orca is a three-step project that involves direct air capture, transport, and geological storage of carbon dioxide powered by renewable geothermal energy (Figure 1) Step 1, Direct Air Capture (DAC). The DAC plant uses eight units called CO_2 collector containers (CC) to capture and concentrate CO_2 from the atmosphere. This is a two-phase process. First, the unit captures atmospheric CO_2 by applying a vacuum temperature swing adsorption process. Air is drawn into the plant using fans and the CO_2 within the air is chemically bound to the sorbent material, henceforth also referred to as "filter". Air with reduced CO_2 concentration is released back into the atmosphere. Second, Once the filter is saturated with CO_2, it is heated to around 100°C using low-grade heat from the geothermal plant as an energy source. The CO_2 is then released from the filter and collected as concentrated gas in the collector unit and the continuous cycle is ready to start again. The captured CO_2 is further processed and liquify to a 99.99% purity. Step 2, Transport. CO_2 is transported in gaseous form via a 3,282 meter-long, buried pipeline running from the DAC capture plant to the geological storage site. The pipe material is plastic and has an inner diameter of 66 mm and a pressure rating for up to 24.5 bar-g. (Figure 2) Step 3, Storage. At the storage site at þrengsli, the CO_2 is mixed with water sourced from two local wells in the injection well before it enters the geological storage reservoir at depths of at least 400 m. During this process, the CO_2 dissolves in the water, ensuring immediate solubility trapping in the reservoir. Subsequently, the CO_2-charged water reacts with divalent cations (such as calcium, magnesium, and iron) dissolved from the basaltic host rock to form stable carbonate minerals that become trapped in the host rock (in-situ carbon mineralization). This storage process known as mineral trapping is one of the most secure CO_2 storage mechanisms. Finally, several monitoring wells, placed at increasing distance from the injection well, are used to confirm that the CO_2 is permanently stored. (Figure 3)
…	

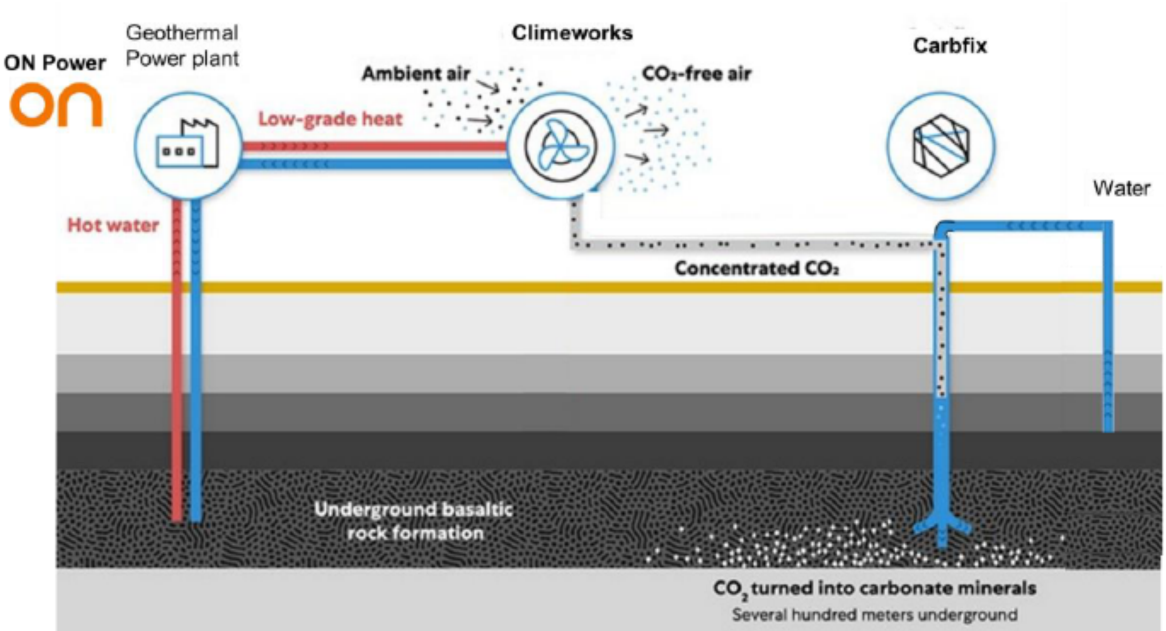


Figure 1. Orca process description (Source: Climeworks).

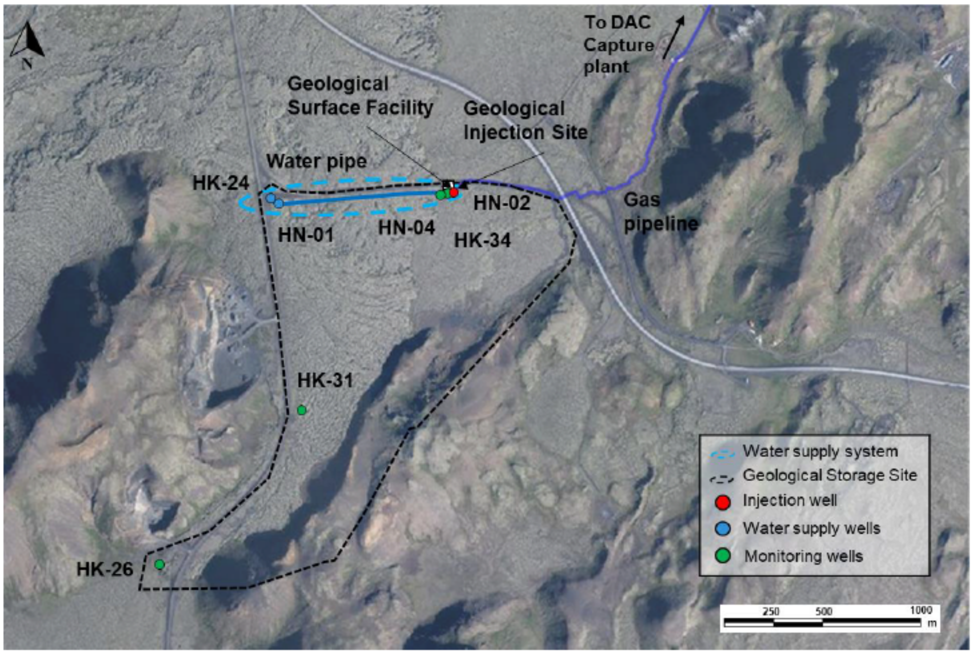


Figure 2. Map of the CO_2 storage facility in Hellisheiði, Iceland.

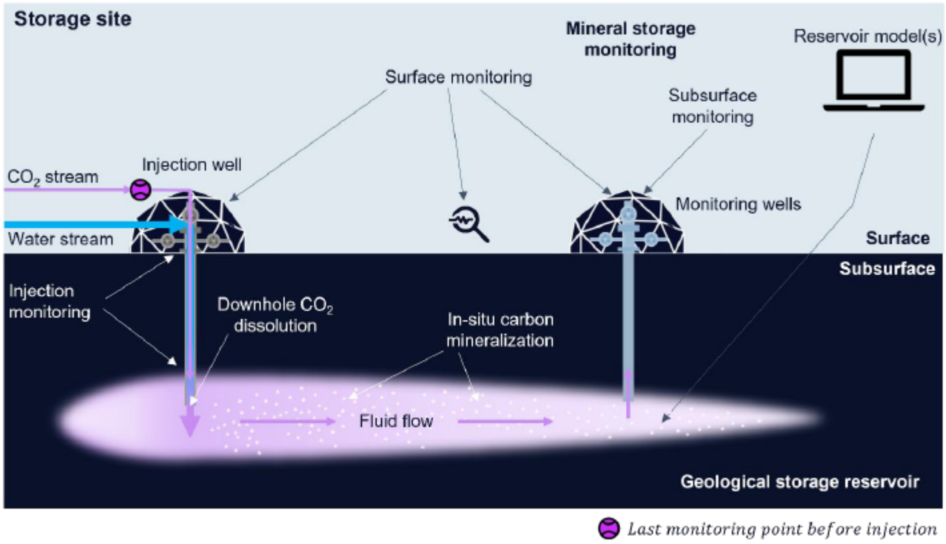


Figure 3. Injection and monitoring system and geological storage reservoir.

3. Application of Puro Standard and Methodology

3.1. Project Boundary

*The information in this section provides a summary of the project-specific **project boundary**.*

Instructions	*Please provide a **summary of the project boundary** according to the methodology section 3. Word limit: 150 words.*
Summary	
The boundaries of the project, defining what is included in emissions and impact assessments, are illustrated in Figure 4. The project boundary includes all three steps and the (direct and indirect) emissions resulting from them. Construction and equipment emissions are included for all three steps. The Orca DAC and storage project does not involve any biomass The physical boundaries of the project include the infrastructure and the vertical and lateral limits of mineralization. The activities of the geothermal power plant are outside of them, and heat and electricity are simply inputs into the project boundary. Similarly, the boundary is on the interface of the atmosphere and the DAC plant, such that atmospheric air is an input and output and not a reservoir included in the project.	
For details	----

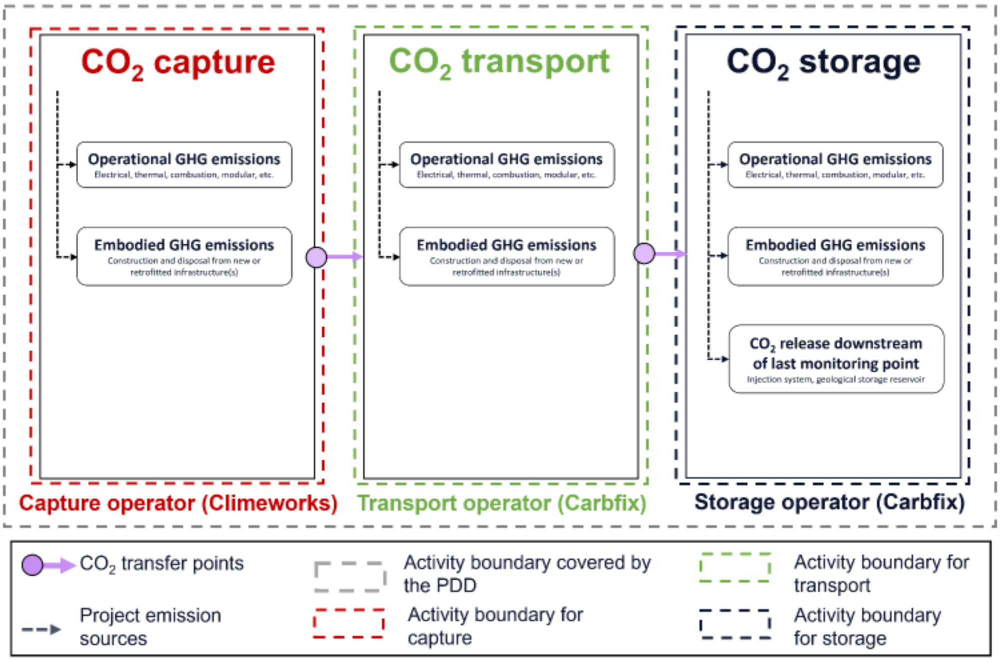


Figure 4. Boundaries of Project Orca (source: Climeworks).

3.2. Baseline

*The information in this section provides a summary of the project-specific **baseline scenario**.*

Instructions	*Please provide a summary of the project-specific baseline scenario. Word limit: 150 words.*
Summary	
The baseline scenario is no Carbon Dioxide Removal and Storage Prior to the construction of Orca, the site was an unused open space with no economic activity and negligible environmental benefits given the small project footprint size and proximity to the existing geothermal power plant. Furthermore, the ground vegetation was grassland, and lacked substantial carbon-sequestering potential. For these reasons, the baseline carbon sequestration is set as zero for all evaluations. Prior to the construction of Orca, the injection site was unused albeit with some infrastructure in place (injection wells, monitoring wells, and water supply wells).	
For details	----

3.3. Demonstration of Additionality

*The information in this section provides a summary of the project-specific **additionality assessment**.*

Instructions	*Please provide a summary of the additionality assessment, baseline, regulatory, financial. Word limit: 150 words.*
Summary	
Baseline additionality: Yes, Orca project is additional and resulting in higher volume of carbon removal than the baseline scenario. Regulatory additionality: Yes, there is no existing regulation mandating Orca project operation. Financial Additionality: Yes, a large investment is needed with no other revenue sources than carbon finance. Orca required a multi-million investment financed by Climeworks with the	

support of long-term Carbon Removal commitments from customers. As a first-of-its-kind industrial scale direct air capture and storage plant, Orca project faces particularly high uncertainty to the returns, linked to the actual CO_2 output and incurring continuous operating costs related to energy, land lease, plant operations and maintenance. Orca required a multi-million investment without any subsidies and the investment is solely relying on Carbon Financing from pioneering companies and individuals that have entered into long-term commitments to remove carbon dioxide from the air to secure geological storage with Orca project.	
For details	Attachment A_Additionality_Orca

3.4. Positive SDG Impacts

*The information in this section provides a summary of the project-specific **Positive SDG Impact description**.*

Instructions	*Please provide a summary of the Positive SDG Impact. Word limit: 150 words.*
SDG Target	*13.0 Climate Action*
SDG Indicator	Tonnes of greenhouse gas emissions removed.
Net Impact on SDG Indicator	Direct Air Capture of CO_2 from the atmosphere and permanent storage through in-situ carbon mineralization resulting in CO_2 removals to durable geological storage. The climate benefit resulting from carbon removal is quantified and certified as CO_2 Removal Certificates (CORCs).
For details	----

3.5. Quantification of Net CO_2 removal and CORC calculation

*The information in this section provides a description of the **quantification of** CO_2 **removals** of the project.*

Instructions	*Please provide a description of the quantification of CO_2 removals according to the methodology section 4. Word limit: 100 words.*
Technical description	
Net CO_2 Removal volume (in tCO_2e) for the Project Orca within the activity boundary and during the monitoring period is calculated by measuring the CO_2 injected - (minus) project emissions - (minus) emissions from construction of equipment amortized over 10 years. If any release of CO_2 from the injection system or geological storage reservoir is detected after the last measurement point, it is quantified and deducted from the CO_2 injected.	
For details	Attachment_B_Quantification-of-CO_2-removals

3.6. Monitoring and Reporting Plan

Instructions	*Please provide a summary of the monitoring plan for the carbon removal activity taking place at the production facility. Word limit: 1000 words.*
Summary of Monitoring Plan	

Different parameters and conditions are monitored throughout Project Orca to ensure safe operation, accurate quantification of CO_2 emitted and stored, and permanence of stored CO_2. The following summarizes the monitoring plan and procedures in place for Project Orca. a. Monitoring Project emissions i. Energy consumption is measured and reported monthly. ii. Sorbent and water use is measured and reported monthly. iii. Construction emissions have been calculated and are amortised monthly over the projects initial ten years. b. Monitoring of the CO_2 injection (Figure 3): i. Mass flow, pressure, and temperature of the gas injection. ii. Mass flow, pressure, and temperature of the water injection. iii. Chemical composition of the CO_2 stream and water supply. iv. Calculation of bubble point pressure of injected mixture from the parameters above and comparison to reservoir pressure to ensure conditions for full solubility trapping are fulfilled. v. CO_2 gas detectors in control and wellhead buildings. c. Monitoring of the geological CO_2 storage reservoir (Figure 2,3): i. Chemical composition of reservoir fluids sampled in monitoring wells ii. Tracer test(s) (injection of tracer(s) into injection well followed by tracer sampling in monitoring wells iii. Numerical reservoir using the data above, monitoring the migration of the injected CO_2 and estimating the degree of mineralization iv. CO_2 surface flux surveys at injection site d. Closure and post-closure monitoring: Lowering/phasing out of monitoring well sampling, updates of reservoir models and surface flux measurements e.

For details	Attachment_C_Monitoring_Plan_ORCA

4. Summary of Social & Environmental Safeguards

The information in this section provides a summary of the project-specific measures taken to avoid and minimize negative social and environmental effects.

4.1. Description of negative social and environmental impacts and risks

Instructions	*Please provide a summary of the social and environmental safeguards of the carbon removal activity taking place at the production facility. Word limit: 500 words*
Summary of Social and Environmental Safeguards	
Personnel safety: Safety analysis (Hazard and Operability Analysis (HAZOP), etc.) is an integral part of the Climeworks project development processes and has been carried out for Orca project. Over the past years Climeworks has gained > 120'000 hours of operational experience with its DAC plants. Internal procedures and tools are clearly documented and communicated (ISO 9001 certified) and the engineering as well as the operative parts of the company are used to delivering according to strict safety rules. Remote control of the plants allows Climeworks to react quickly to errors and ensure safety.	

To protect personnel continuous monitoring and detection of unexpected CO_2 release is ensured by CO_2 sensors that detect CO_2 accumulation in the wellhead building and the Orca Hut. Check valves located at the injection wellhead for both the gas and water pipes ensure that no backflow from the injection well can occur. The process cannot build up pressure within the containers without opening the doors and stopping the process automatically. None of the safety measures for the known failure scenarios require an active supply of electricity or cooling, ensuring safe operation in all cases.

Environmental safeguards:
Permanence and safety of geological CO_2**.**
The Carbfix method inherently minimizes the risk of CO_2 leakage. The feasibility of geological CO_2 mineralization using the Carbfix method has been proven in two different projects and geological reservoirs: The Carbfix pilot at þrengsli, Iceland (2012) and nearby at the Hellisheiði power plant, Iceland (ongoing since 2014). Orca is using the reservoir of the prior Carbfix pilot project exclusively. The Carbfix method as well as the monitoring of the CO_2 in the reservoir by specifically developed methods, reservoir characterization has been comprehensively described and discussed in scientific literature.

Permits for plant installation and operation are managed by the local permitting agencies according to local regulation (e.g. building codes, environmental law). The local regulation for CO_2 storage sites in Iceland is adopted from the EU CCS directive. The competent authority is the Environment Agency of Iceland (EAI). Furthermore, Carbfix has received the opinion on the Environmental Impact Assessment for storage activities at this site from the National Planning Agency of Iceland.

Other environmental aspects ?
N/A

For details	Environmental Impact Assessment (EIA) for storage activities (Icelandic): https://www.skipulag.is/media/attachments/Umhverfismat/1986/Umhverfismatssk%C3%BDrsla%20ni%C3%Bourd%C3%A6ling%20greinarger%C3%Bo.pdf Opinion by the National Planning Agency of Iceland on the EIA (Icelandic): https://www.skipulag.is/media/attachments/Umhverfismat/2065/Ni%C3%B0urd%C3%A6ling%20CO2%20%C3%A1%20Hellishei%C3%B0i.%20%C3%81LIT.pdf Scientific literature related to Carbfix: https://www.carbfix.com/scientific-papers Scientific study directly related to the sustainability of the Orca project: https://www.nature.com/articles/s41560-020-00771-9

5. Summary of Stakeholder Engagement

Instructions	*Please provide a summary of the stakeholder engagement of the carbon removal activity taking place for the production facility. Word limit: 300 words.*
Summary of stakeholder engagement	
The project partners engage on a regular basis with all relevant project stakeholders in Iceland. Stakeholders include environmental NGOs, communities, policymakers and politicians, civil society organizations, unions, industry associations, relevant permitting agencies, and additional interested parties. Given the pre-existing relationships between Carbfix/ON Power and local stakeholders, engagements have taken place both in an informal and formal manner. These engagements took place parallel to permitting procedures overseen by the local authorities. Following initial site characterization, Carbfix and Climeworks developed an engagement plan for Orca. Representatives of all identified stakeholder groups were engaged and consulted on Orca via Carbfix in cooperation with Climeworks. In-depth formal presentations of the Orca project were given by the Carbfix team to all interested stakeholder groups (March – May 2021), including a tour of the Orca construction site. Carbfix then made a formal introduction for Climeworks to key civil society actors in summer 2021. Climeworks hosted a round of introductory, informal in-person meetings in Reykjavik in August 2021 to solicit initial feedback on Orca and future plans in Iceland. A total of 8 bilateral meetings were held over a period of 4 days. Feedback was internally presented to the Orca project team, assessed, and integrated where appropriate. Interested stakeholders were also able to attend the launch event of Orca in September 2021. Engagements continue as part of this and other projects in Iceland. In addition, the project partners continue to inform the broader public via regular communication efforts through Climeworks' and Carbfix' communications departments, press, social media, website, and newsletters throughout the construction phase of Orca, and its current operation.	
For details	Attachment_D: Stakeholder engagement report

6. Attachments

Attachment index	Attachment name	No of pages
A	Attachment_A_Additionality_Assessment_Orca	4
B	Attachment_B_Quantification_of_CO_2_Removal	12
C	Attachment_C:_Monitoring_Plan_ORCA	20
D	Attachment_D: Stakeholder engagement report	2

Add rows as needed

6.1. Attachment A: Additionality Assessment.

See separate document

6.2. Attachment B: Quantification of CO_2 Removals.

See separate document

6.3. Attachment C: Monitoring Plan.

See separate document

6.4. Attachment D: Stakeholder Engagement Report

See separate document

Baseline and Additionality Assessment

The baseline and additionality assessment is a requirement for eligibility under the Puro Standard. The assessment is made by the CO_2 Removal Supplier and verified by the independent 3rd party auditor. The assessment made in this document will be publicly available in the Puro Registry.

The Puro Standard only certifies durable carbon removals from the atmosphere that are net-negative and does not certify emissions reductions or avoidance. The CORCs (Carbon dioxide removal certificates), issued therefore represent a net carbon removal (1 tCO2eq. net) from the atmosphere to a durable storage of minimum 100 years, and for mineralization and geological storage minimum 1000 years. From the stored gross CO_2 volume are subtracted any supply-chain emissions from the project, any re-emissions over the guaranteed storage time, and any baseline removals taking place in a baseline scenarios.

The CO_2 Removal Supplier must in this assessment:

- **Define** and quantify all reasonable **baseline alternatives** to the proposed project activity to remove carbon with carbon financing. A baseline is a scenario that reasonably represents the natural and anthropogenic carbon removals to a permanent storage (storage durability over 100 years or 1000 years) in the absence of the carbon removal activity proposed by the CO_2 Removal Supplier. Although anthropogenic emissions may take place in the baseline scenarios, these emissions do not constitute a reference point for the quantification of CORCs (only the baseline removals do).
- Demonstrate **carbon additionality to the baseline**, meaning that the project must convincingly demonstrate that it is resulting to higher volumes of carbon removals than the likely baseline alternatives (question A1.).
- Demonstrate **regulatory additionality,** meaning that the project is not required by existing laws, regulations, or other binding obligations (question A2.).
- Demonstrate **financial additionality**, meaning that the CO_2 removals achieved are a result of carbon finance and that the project activity would not be economically viable without the carbon finance. The project activity can have substantial other non-carbon income sources, if the carbon finance through CORCs is significant for the economic viability of the project. To demonstrate financial additionality, CO2 removal Supplier must provide the responses in this form and must be able to provide full project financials for verification.

Reference documents: Puro Standard general Rules v3.1, and Additionality Assessment requirements

Activity name	Activity description	Removals to storage (1000+ yr) due to project activity (human activity)	Natural removals to storage (1000+ yr), not man-made
Baseline	The baseline scenario is no Carbon Dioxide Removal and Storage	None	None
Project activity: **Orca Carbon Dioxide Removal with Direct Air Capture + Storage**	Project activity is additional, removing Carbon Dioxide from the air.	26 ktons	None

A1. Does the project lead to higher volumes of carbon removal than the baseline?	Yes / No
Every ton of carbon dioxide removed from the air by Orca is a ton immediately not contributing to global warming	Yes

A2. Is the project required by existing laws, regulations, or other binding obligations ?	Yes / No
The Orca DAC plant was not required by existing laws, regulations or other binding obligations	No

A3. Is the project first-of-its-kind?	Yes / No
Orca, is the world's first climate-positive direct air capture and storage plant, making direct air capture and storage a reality.	Yes

A4. Is the project dependent on carbon finance?	Yes / No
Orca is solely relying on Carbon Financing from pioneering companies and individuals that have entered long-term commitments to remove carbon dioxide from the air and help rapidly scale up this much-needed climate technology in the years to come. Carbon Finance is essential to ramp up capture capacity significantly, as will be required to meet the strong market demand for carbon dioxide removals.	Yes

A5. Does the project need a large investment to achieve carbon removal ?	Yes / No
Orca required a multi-million investment financed by Climeworks with the support of long-term Carbon Removal commitments from customers.	Yes

A6. If investment is needed, is/was carbon finance considered when the investment decision is/was made?	Yes / No
While, Orca has been pre-financed, investment in terms of carbon finance is generally still required and will be required in the future.	Yes

Some projects may demonstrate additionality through simple cost analysis: this is applicable for projects where ex-ante investment analysis is not applicable, because a large investment is not needed. Example of such project could be charcoal producers starting to produce biochar for soil applications using existing equipment with minor adaptations.

Financial Additionality – large investment is not needed (Answer to A5 is "no")	Project response
Please describe adaptations needed and the related cost items and include evidence in attachment.	N/A
Please summarize the simple cost analysis here and provide additional calculation spreadsheet in attachment. All formulas used in the spreadsheet shall be readable to the verifier and all relevant cells shall be viewable and unprotected. Mark confidential when needed.	N/A

If large investment is needed, CO_2 Removal Suppliers can be guided by the CDM Methodological Tool 27 of the UNFCCC Clean Development Mechanism "Investment Analysis" to demonstrate financial additionality.

Financial Additionality – large investment is needed (Answer to A5 is "yes")	Project response
Please show your calculations to determine the benchmark rate for either equity IRR or WACC, whichever you are using. Please include documentation of how the rate is suitable for the technology and region.	N/A
Please state how CORC revenues change the expected IRR or NPV of the project.	As the first industrial scale direct air capture and storage plant, Orca is enabling the sale of Carbon Dioxide Removal Services to pioneering customers, which is required to scale up the technology and provide Climeworks with the field experience necessary to lower costs in the future and maximize the volume of tons of CO_2 removed from the atmosphere. As a first-of-its-kind investment there is particularly high uncertainty to the returns, linked to the actual operating costs and CO_2 output. Orca required a multi-million investment without any subsidies and is incurring continuous operating costs related to energy, land lease, plant operations and maintenance. Hence all investment would be lost without carbon credit revenues.
Please conduct a sensitivity analysis in relation to the investment analysis and summarize the results here.	N/A
Please provide full calculation spreadsheet file as an attachment. All formulas used in the spreadsheet shall be readable to the verifier and all relevant cells shall be viewable and unprotected. Mark confidential when needed.	A confidential spreadsheet has been provided for verification

I hereby declare that all information provided is truthful and precise to the best of my knowledge.

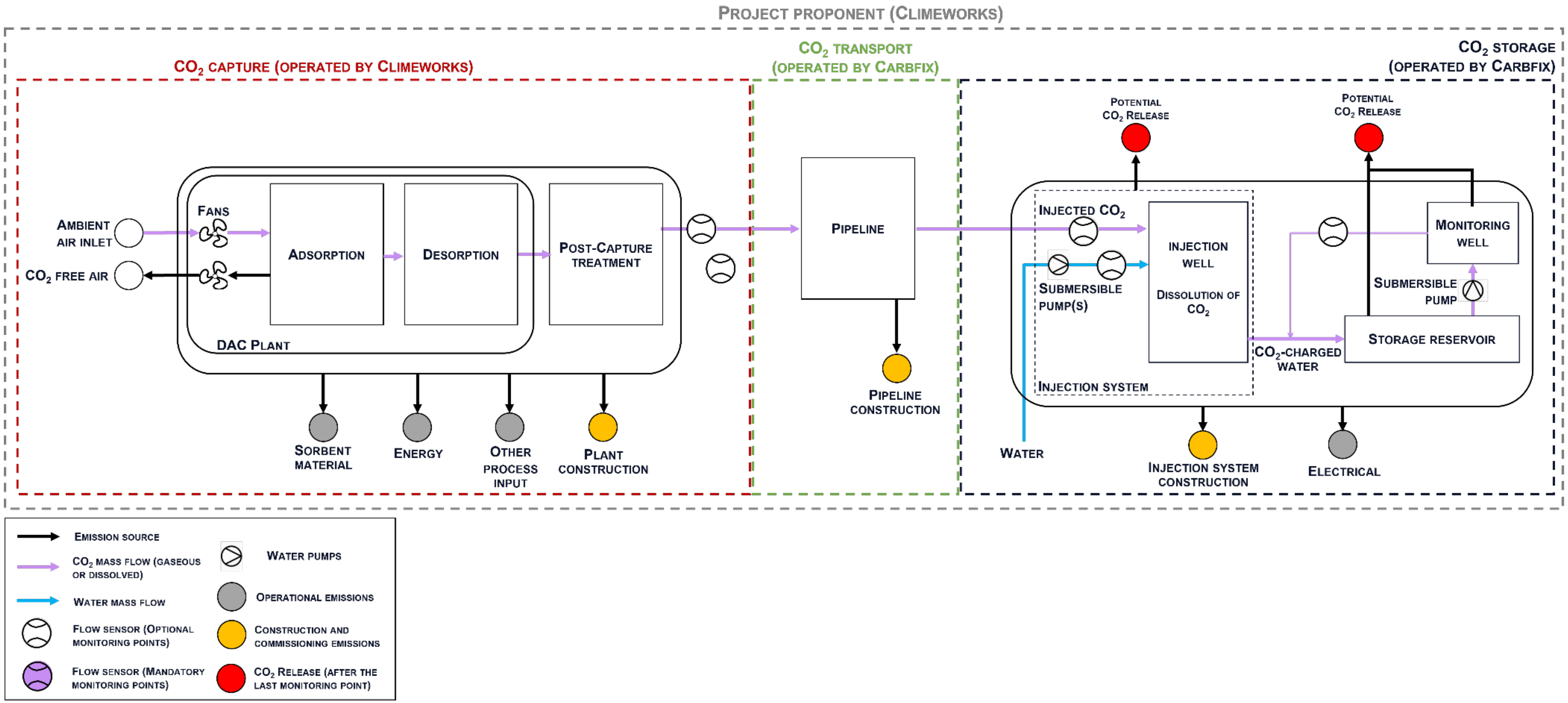
Georgios Emmanouil

Georgios Emmanouil, Commercial Finance Manager, Climeworks AG

Date, Place: 28/02/2024, Zurich, Switzerland

Attachment B – Quantification

Basic Information	
Project name	Orca Project Orca is a Direct Air Capture and Mineral storage project owned by Climeworks and operated by Climeworks and partner Carbfix. Project Orca captures CO_2 from the atmosphere using Climeworks' Direct Air Capture and stores the CO_2 permanently underground using Carbfix's in-situ carbon mineralization. The plant is located outside of Reykjavik, Iceland at the Hellisheiði Geothermal Power Station.
Date of Version	26.02.2024
Project Proponent(s)	Climeworks AG
Project Operator(s)	Climeworks AG, Carbfix hf
MRV cycle	1
Certifying body	Puro
Prepared by	Climeworks AG Birchstrasse 155 CH - 8050 Zurich +41 (0)44 533 29 99 contact@climeworks.com
Aknowledgement	To the best of our knowledge, this presents the world's first certification of a Direct Air Capture and Storage project ever. This milestone wouldn't have been achievable without extensive collaboration between Carbfix and Climeworks. Whilst Climeworks is the sole project proponent listed, we are grateful and proud to have achieved this milestone together with Carbfix. Carbfix



Process flow diagram of the full chain carbon removal and mineral storage. The diagram shows the monitoring points, the project emission sources, potential CO_2 release, and the project construction and commissioning

A schematic of CO_2 flow in Project Orca with the step and project boundaries identified. CO_2 moves from DAC in (step 1) to the transport (step 2) and geological storage (step 3).

Direct Air Capture and post-capture treatment refers to the infrastructure and operations required to capture, liquefy, and pressurize CO_2 in step 1 including water, heat, electricity, and sorbent filter material. Transport includes the pipeline infrastructure used to transport CO_2 between capture and storage. Storage includes the infrastructure and operations involved in injection, storage, and monitoring including electricity and water supply.

1. Emissions Calculation of Project Scenario

1.1 Baseline Scenario

Prior to the construction of Orca, the site was an unused open space with no economic activity and negligible environmental benefits given the small project footprint size and proximity to the existing geothermal power plant. Furthermore, the ground vegetation was grassland, and lacked substantial carbon-sequestering potential. For these reasons, the baseline is set as zero for all evaluations.

Prior to the construction of Orca, the injection site was unused albeit with all infrastructure in place (injection wells, monitoring wells, and water supply wells).

1.2 Emissions Calculation Overview and Concept

As the purpose of the project is to lower atmospheric greenhouse gas (GHG) concentrations to fight climate change and the fact that carbon credits will be issued from this project, it is vital that the project has a substantial *net* reduction of GHGs and that emissions are calculated accurately. The carbon dioxide removal (CDR) quantification in this methodology is designed to minimize the possibility of overestimation due to measurement uncertainties or omitted emission sources. To bring all GHGs from emissions sources into equal and comparable units with CO_2 captured and stored, GHGs have been converted to Global Warming Potential (GWP) units reported as CO_2 equivalents over a 100 year timeframe and tonnes of CO_2.

The following subsections of the document break down the methods of how Carbon Dioxide Removal (CDR) services is quantified as ($mCO_{2,credited,y}$). Additionally described is how releases and emissions are measured, calculated, and monitored for each of the steps defined in the project boundary section.

1.3 Calculation of CO_2 credited during monitoring period

The net CDR ($mCO_{2,credited,y}$) is reported for the given monitoring period as the total amount of CO_2 injected in the geological storage reservoir ($mCO_{2,\text{injected},y}$) minus; the CO_2 released ($mCO_{2,\text{released},y}$), emissions from operation ($mCO_{2eq,\text{project,operation},y}$), and the embodied emissions ($mCO_{2eq,\text{project,embodied},y}$) from construction and disposal of project Orca as scheduled in the installment plan (see section 1.7). This concept is illustrated in Equation 1. Each term in Equation 1 is explained in a subsection where additional parameters are defined and methodology equations are simplified for the application of Project Orca. A final section summarizes the equations adapted for Project Orca and their terms.

$$mCO_{2,credited,y} = mCO_{2,\text{injected},y} - mCO_{2,\text{released},y} - mCO_{2eq,\text{project,operation},y} - mCO_{2eq,\text{project,embodied},y}$$

Calculation of CO_2 credited during monitoring period (y): Equation. 1

Carbon Dioxide Removal by Direct Air Capture: Equation 1

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 1

where			
$mCO_{2,credited,y}$	=	total amount of CO_2 credited in own accounting or sold/transacted to third parties in monitoring period y.	tonne (tCO_2)

$mCO_{2,\text{injected},y}$	=	total amount of CO_2 injected in the geological storage in monitoring period y, determined at the last monitoring point.	tonne (tCO_2)
$mCO_{2,\text{released},y}$	=	total amount of CO_2 released downstream of the last monitoring point at the storage site in monitoring period y.	tonne (tCO_2)
$mCO_{2eq,\text{project,operation},y}$	=	total GHG emissions due to project operations of the CDR value chain (DAC, Transport, and Storage) in monitoring period y.	tonne (tCO_2)
$mCO_{2eq,\text{project,embodied},y}$	=	total GHG emissions due to construction and disposal of the CDR value chain (DAC, Transport, and Storage) scheduled for monitoring period y.	tonne (tCO_2)
y	=	monitoring period during which credits are produced	days

1.4 Calculation of Total CO_2 injected during monitoring period

Equation 2 summarizes the calculation for the total mass of CO_2 injected for the project during the monitoring period (y) as the summation of injected CO_2 at all wells (*i*). Project Orca only has one injection well and therefore (*i*) is omitted from methodology equations and Equations 2 and 3 from the methodology are simplified to Equation 2.a.

Equation 2 shows that the total amount of CO_2 injected ($mCO_{2,i,y}$) into the geological storage reservoir at each well is determined from the mass flow rate ($\dot{m}_{injected}$), measured at the last measurement point of the injection system, multiplied by the weight fraction ($x_{CO2,i}$) of the injection stream.

$$mCO_{2,injected,y} = \sum_i mCO_{2,i,y}$$

Calculation of Total CO_2 injected during monitoring period: Equation. 2

Carbon Dioxide Removal by Direct Air Capture: Equation 2

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 2

$$mCO_{2,i,y} = \int_0^y \dot{m}_{CO2,i} \cdot x_{CO2,i} dt$$

Calculation of Total CO_2 injected at injection well (*i*): Equation. 3

Carbon Dioxide Removal by Direct Air Capture: Equation 3

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 3

where			
$mCO_{2,i,y}$	=	Mass of CO_2 injected at each injection well in monitoring period y, determined at the last monitoring point.	tonne (tCO_2)
$\dot{m}_{CO2,i}$	=	The mass flow rate of the CO_2 stream at the injection well, metered continuously	tonne/sec (t/s)
$x_{CO2,i}$	=	The CO_2 weight fraction of the injection stream entering the injection well.	W_{CO2}/ W_{stream} (unitless)
dt	=	Numerical integration over the monitoring period y.	seconds (s)
i	=	Injection well(s).	unitless

Project Orca only has one well site, and thus Equation 2 and 3 can be simplified as:

$$mCO_{2,injected,y} = mCO_{2,y} = \int_0^y \dot{m}_{CO2} \cdot x_{CO2} dt$$

Simplified Calculation of Total CO_2 injected during monitoring period: Equation. 2.a

where			
$\dot{m}_{CO2}$	=	the mass flow rate of the CO_2 stream at the injection well, metered continuously	tonne/sec (t/s)
x_{CO2}	=	the CO_2 weight fraction of the injection stream entering the injection well, determined from liquefaction unit manufacture's output	W_{CO2}/ W_{stream} (unitless)
dt	=	numerical integration over the period (*y)*	seconds (s)

<u>Measurement Methodology</u>

The fraction of CO_2 in this stream (x_{CO2}) is adopted from the quality of CO_2 produced by the liquefaction unit at the capture site, 99.99%. This CO_2 stream remains pressurized from liquefaction to injection, eliminating any physical chance for impurities to mix with the stream without changing pressure readings. Therefore, the quality of the CO_2 stream is considered consistent between liquefaction up until it is mixed with water within the well.

Proper function of the liquefaction unit is monitored with twice-annual samples sent to an accredited lab. The samples verify the accuracy of a 99.99% injection stream purity as guaranteed by manufacturers descriptions.

1.5 Calculation of total CO_2 Released During Release Events

The CDR reported during the monitoring period is based on the quantity of CO_2 injected minus emissions and releases. Since the injection quantity is measured at the injection well, fugitive or vented emissions that may have occurred between initial capture and subsequent injection are already accounted for. Therefore, only releases that occur after the injection point need to be quantified and subtracted from the injection quantity.

Release events include planned and unplanned events that can occur for various reasons. Each release event is expected to be unique in how, where, and why it occurred and therefore when a release occurs, it will be documented in the Monitoring Report. The Monitoring Report will outline the methods used to quantify the released CO_2, as methods for each event will be different.

The release of CO_2 after the last measurement point distinguishes between the release from the injection system and the geological storage reservoir.

Equation 4 describes how the total mass of CO_2 released is the sum of all release events occurring in the injection and geologic storage systems during the monitoring period (y).

$$mCO_{2,released,y} = mCO_{2,released,injection\ system,y} + mCO_{2,released,geological\ storage,y}$$

where

$$mCO_{2,released,injection\ system,y} = \sum_j mCO_{2,\ release\ event,injection\ system,j}$$

$$mCO_{2,released,geological\ storage,y} = \sum_k mCO_{2,\ release\ event,geological\ storage,k}$$

=

$$mCO_{2,released,y} = \sum_j mCO_{2,\ release\ event,injection\ system,j} + \sum_k mCO_{2,\ release\ event,geological\ storage,k}$$

Calculation of total CO_2 Released During Release Events: Equation. 4

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 6

where			
$mCO_{2,\ release\ event,injection\ system,j}$	=	Intentional or unintentional release of CO_2 from the injection system during event j	tonne (tCO_2)
$mCO_{2,\ release\ event,geological\ storage,k}$	=	Intentional or unintentional release of CO_2 downstream from the last monitoring point within the storage reservoir during event *k*.	tonne (tCO_2)
j	=	CO_2 release event from the Injection System.	unitless
k	=	CO_2 release event from the Geological Storage Reservoir.	unitless

<u>Measurement Methodology</u>

No CO_2 release from the injection system is expected if the system is properly operated. As such the ex-ante estimate is 0. CO_2 release from the injection system will, however, be monitored by CO_2 sensors located inside the control room and the injection igloo. If CO_2 is detected, then the project proponent shall quantify the amount of CO_2 that is being released and document it in the monitoring report.

No CO_2 release from the storage reservoir is expected if the system is properly operated. No intentional CO_2 release from the geological storage reservoir by the production of CO_2 fluid by the monitoring wells is expected, as the fluid will be reinjected into the injection well. Unintentional CO_2 release from the geological storage reservoir will, however, be monitored by surface flux measurements. If CO_2 is detected, then the project proponent shall quantify the amount of CO_2 that is being released and follow the mitigation measures. As such, the ex-ante estimate is 0.

1.6 Calculation of GHG Emissions from Project Operation

Equation 5 describes how the greenhouse gas emissions (GHG) resulting from operating Project Orca are calculated. Operational emissions are calculated for each project phase (capture, transport, storage) as the sum of all emitting activities in that phase calculated as the product of the intensity of the activity and it's emitting factor. Project operational emissions are then calculated as the sum of operational emissions across all project phases (capture, transport, storage).

The emitting factor is a literature-derived value and represents the total GHG impacts of the activity represented as carbon dioxide equivalent (CO_{2eq}) and reported in tonnes of CO_2 to maintain consistent units throughout the project calculations

$$mCO_{2eq,\text{project,operation},y} = \sum_p mCO_{2eq,p,operation,y}$$

where

$$mCO_{2eq,p,operation,y} = \sum_z \left(I_{z,p,y} \cdot ef_{z,p,y}\right)$$

=

$$mCO_{2eq,\text{project,operation},y} = \sum_p \sum_z \left(I_{z,p,y} \cdot ef_{z,p,y}\right)$$

GHG Emissions from Project Operation: Equation. 5

Carbon Dioxide Removal by Direct Air Capture: Equation 4

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 4

where			
$mCO_{2eq,p,operation,y}$	=	Operational GHG's for project phase (p) during monitoring period (y)	tonne (tCO_2)
p	=	Process Steps, these include the capture, transport, and storage steps in the CDR chain. If mixing of CO_2 stream occurs within the storage step, the storage can be further divided into the surface conditioning and injection facility steps.	unitless
z	=	Process Input	unitless
$I_{z,p,y}$	=	Intensity of consumption of a process input.	Quantity (qty)

$ef_{z,p,y}$	=	Emission factor or emission rate of a given pollutant relative to the intensity of a specific process input	tonne/quantity (tCO_2 / qty)

Equation 5 from the methodology is adapted in Equation 5.a to reflect the operational inputs of Project Orca.

$$mCO_{2eq,capture,operation,y} = \left(I_{electricity,capture,y} \cdot ef_{electricity,capture,y}\right) + \left(I_{heat,capture,y} \cdot ef_{heat,capture,y}\right) + \left(I_{sorbent,capture,y} \cdot ef_{sorbent,capture,y}\right) + \left(I_{other\ process\ input,capture,y} \cdot ef_{other\ process\ input,capture,y}\right)$$

$$mCO_{2eq,storage,operation,y} = \left(I_{electricity,storage,y} \cdot ef_{electricity,storage,y}\right)$$

$$mCO_{2eq,\text{project,operation},y} = \left[\left(I_{electricity,capture,y} \cdot ef_{electricity,capture,y}\right) + \left(I_{heat,capture,y} \cdot ef_{heat,capture,y}\right) + \left(I_{sorbent,capture,y} \cdot ef_{sorbent,capture,y}\right) + \left(I_{other\ process\ input,capture,y} \cdot ef_{other\ process\ input,capture,y}\right)\right]_{capture} + \left[\left(I_{electricity,storage,y} \cdot ef_{electricity,storage,y}\right)\right]_{storage}$$

GHG Emissions from Project Operation: Equation. 5.a

$I_{electricity,capture,y}$	=	Operational Electricity used in capture, in period (y)	MWh
$ef_{electricity,capture,y}$	=	Emission factor of electricity used	tCO_2/MWh
$I_{heat,capture,y}$	=	Operational heat used during capture, in period (y)	MWh
$ef_{heat,capture,y}$	=	Emissions factor for heat use	tCO_2/MWh
$I_{sorbent,capture,y}$	=	Quantity sorbent used to operate capture, in period (y).	tonne (t/y)
$ef_{sorbent,capture,y}$	=	Emissions factor for sorbent	tCO_2/ $t_{sorbent}$
$I_{other\ process\ input,capture,y}$	=	Quantity water used to operate capture, in period (y).	tonne (t_{water})
$ef_{other\ process\ input,capture,y}$	=	Emissions factor for water	tCO_2/ t_{water}
$I_{electricity,storage,y}$	=	Operational Electricity used in storage, in period (y)	MWh
$ef_{electricity,storage,y}$	=	Emission factor of electricity used	tCO_2/MWh
$I_{electricity,capture,y}$	=	Operational Electricity used in capture, in period (y)	MWh

<u>Measurement Methodology</u>

The measurement methodology for operational emissions is divided into project phases as follows.

Measurement Methodology Capture:

The operational capture emissions are the sum of the emissions linked to the capture operations. Project Orca has emissions due to the electricity, heat, sorbent, and water usage operational inputs for the capture phase.

Capture Energy Emissions:

Orca relies on the supply of electrical and thermal energy by the local energy utility ON Power. The relevant ex-ante emission factors for heat and electricity generation at the Hellisheiði Geothermal Power Plant are in accordance with the assessment and methodology in the peer reviewed study for the Hellisheiði power station (Karlsdottira et al., 2020).

The quantity of heat and electricity imported for the operation of the DAC and post-capture treatment facilities will be according to the supplier's monthly invoices.

Capture Sorbent Emissions:

Climeworks' temperature vacuum swing (TVS) process is operated with a sorbent material. The sorbent material can be regenerated several thousand times but must be replaced at the end of its lifetime, leading to embedded GHG emissions from material consumption. The sorbent emissions are determined based on a replacement rate of sorbent per tonne of CO_2 captured. This replacement rate is based on 10 years of operational data collected from 16 Climeworks DAC plants at geographically diverse locations, including Iceland. The emissions estimate also accounts for the specific embedded sorbent emissions in both sorbent production and recycling/disposal.

For sorbent material, the emission factor (ef) for sorbent was derived from an independent analysis of Climeworks' materials data. The analysis adhered to ISO 14044 standards and provides a conservative estimate compared to the value for similar sorbent material stated in peer reviewed academic literature (Deutz & Bardow, 2020). This value is listed in the Monitoring Report.

Capture Other Input Emissions:

The ex-ante assessment of other process inputs needed for the operation of the DAC technology and post-capture treatment facilities resulted in the inclusion of cooling water as a non-negligible process input. Cooling water is used during the TVS process. For cooling water use, the emission factor is in accordance to the assessment and methodology in the peer reviewed study for the Hellisheiði power station (Karlsdottir et al., 2020).

Water will be procured and billed according to actual consumption, based on direct and continuous flow rate measurements and periodical readings. The cooling water use is minimized by internal reuse within the DAC plant based on counter-current heat exchange and by recycling the cooling water in the downstream CO_2 injection.

Measurement Methodology Transport:

Project Orca has no operational emission associated to the transport phase. During the post-capture treatment the CO_2 is compressed as liquid to a storage tank and then vaporized prior to delivery to the transport pipe. The CO_2 is supplied from the capture plant to the transport pipe at sufficient pressure to overcome the pressure drop encountered in the transport pipe and thus deliver the CO_2 at the required injection system operational pressure.

Measurement Methodology Storage:

The electricity usage for the CO_2 storage operation includes two submersible pumps for the water supply, one submersible pump for the monitoring well, the compressor inside the control room, and the heater in the injection igloo. The system has two operation modes, baseload and peak utilization based on the supply or not of CO_2 from the capture step.

Storage Energy Emissions:

The storage operation for Orca relies on the supply of electrical energy by the local energy utility ON Power. The quantity of electricity imported for the operation of the injection and monitoring facilities will be according to the supplier's invoices. The emission factor for electricity generation at the Hellisheiði Geothermal Power Plant based on an LCA assessment of the project specific energy sources according to the energy supplier, that have also been published in peer reviewed literature (Deutz & Bardow, 2020).

1.7 Calculation of Embodied GHG Emissions from Construction and Disposal

Emission calculations resulting from construction and disposal ($mCO_{2eq,\text{project,embodied},y}$) of the capture, transport, and storage facilities are based on third-party life cycle assessments. These emissions are totaled across project phases as shown in Equation 6 and scheduled to be deducted from total injected CO_2 quantities over 8 of the 12-year project period as outlined in Table 1.

$$mCO_{2eq,\text{project,embodied},y} = \sum_{p} mCO_{2eq,p,embodied,y}$$

Calculation of GHG Emissions from Embodied Emissions Equation. 6

Carbon Dioxide Removal by Direct Air Capture: Equation 5

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 5

where			
$mCO_{2eq,p,embodied,y}$	=	Embodied GHG emissions due to construction and disposal of phase (p) facilities as scheduled for monitoring period (y)	tonne (tCO_2)

Embodied emissions are not deducted the first two years while production is ramping up and potential modifications are made to the facility that would alter the total ($mCO_{2eq,\text{project,embodied},y}$) value. Similarly, the last two years of the project are void of ($mCO_{2eq,\text{project,embodied},y}$) deductions to accommodate any additional emissions that may have arisen though out prior years.

Table 1 Construction and Disposal Embodied Emissions Installment Schedule

Year 20-	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30	'31	'32	Total
% deducted	0	0	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	0	0	100%

<u>Measurement Methodology</u>

Emissions from the construction and disposal are calculated based on to third-party cradle-to-grave LCA assessments, following ISO 14040/14044 guidelines. The analyses include all embodied emissions related to the construction and disposal of Project Orca including capture, transport, and storage facilities. This includes:

- Infrastructure, materials, and activities during the construction of Orca
- Disposal of materials and activities during the deconstruction of Orca

Researchers at the University of Aachen, Germany, performed an independent Life Cycle Assessment (LCA) of Orca's CO_2 capture phase (*Deutz, Bardow, 2021*).

The analysis for the CO_2 transport and CO_2 storage was subcontracted by Carbfix and performed by KPMG.

The LCA's are based on operational data provided by Climeworks and Carbfix and are supplied in supplementary documentation.

1.8 Summary of Emissions Equations and Parameters

The following summarized the equations discussed in sections above as they have been simplified to reflect the conditions of Orca. Parameters are also summarized.

$$mCO_{2,credited,y} = mCO_{2,\text{injected},y} - mCO_{2,\text{released},y} - mCO_{2eq,\text{project,operation},y} - mCO_{2eq,\text{project,embodied},y}$$ Calculation of CO_2 credited during monitoring period (y): Equation. 1 Carbon Dioxide Removal by Direct Air Capture: Equation 1 Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 1
$$mCO_{2,injected,y} = \int_0^y \dot{m}_{CO2} \cdot (x_{CO2})dt$$ Simplified Calculation of Total CO_2 injected during monitoring period: Equation. 2.a
$$mCO_{2,released,y} = \sum_j mCO_{2,\,release\ event,injection\ system,j} + \sum_k mCO_{2,\,release\ event,geological\ storage,k}$$ Calculation of total CO_2 Released During Release Events: Equation. 4 Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 6
$$mCO_{2eq,\text{project,operation},y} = \left[\left(I_{electricity,capture,y} \cdot ef_{electricity,capture,y}\right) + \left(I_{heat,capture,y} \cdot ef_{heat,capture,y}\right) + \left(I_{sorbent,capture,y} \cdot ef_{sorbent,capture,y}\right) + \left(I_{other\ process\ input,capture,y} \cdot ef_{other\ process\ input,capture,y}\right)\right]_{capture} + \left[\left(I_{electricity,storage,y} \cdot ef_{electricity,storage,y}\right)\right]_{storage}$$ GHG Emissions from Project Operation: Equation. 5.a
$$mCO_{2eq,\text{project,embodied},y} = \sum_p mCO_{2eq,p,emboddied,y}$$ Calculation of GHG Emissions from Embodied Emissions Equation. 6 Carbon Dioxide Removal by Direct Air Capture: Equation 5 Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 5

Where			
$mCO_{2,credited,y}$	=	total amount of CO_2 credited in own accounting or sold/transacted to third parties in monitoring period y.	tonne (tCO_2)
$mCO_{2,\text{injected},y}$	=	total amount of CO_2 injected in the geological storage in monitoring period y, determined at the last monitoring point.	tonne (tCO_2)
$mCO_{2,\text{released},y}$	=	total amount of CO_2 released downstream of the last monitoring point at the storage site in monitoring period y.	tonne (tCO_2)
$mCO_{2eq,\text{project,operation},y}$	=	total GHG emissions due to project operations of the CDR value chain (DAC, transport, and storage) in monitoring period y.	tonne (tCO_2)
$mCO_{2eq,\text{project,embodied},y}$	=	total GHG emissions due to construction and disposal of the CDR value chain (DAC, transport, and storage) scheduled for monitoring period *y*.	tonne (tCO_2)
y	=	monitoring period during which credits are produced	Days
$\dot{m}_{CO2}$	=	the mass flow rate of the CO_2 stream at the injection well, metered continuously	tonne/sec (t/s)
x_{CO2}	=	the CO_2 weight fraction of the injection stream entering the injection well, determined from liquefaction unit manufacture's output	W_{CO2}/ W_{stream} (unitless)
dt	=	numerical integration over the period (*y)*	seconds (s)
$mCO_{2,\,release\ event,injection\ system,j}$	=	Intentional or unintentional release of CO_2 from the injection system during event j	tonne (tCO_2)
$mCO_{2,\,release\ event,geological\ storage,k}$	=	Intentional or unintentional release of CO_2 downstream from the last monitoring point within the storage reservoir during event *k.*	tonne (tCO_2)
j	=	CO_2 release event from the Injection System.	unitless
k	=	CO_2 release event from the Geological Storage Reservoir.	unitless
p	=	Process Steps, these include the capture, transport, and storage steps in the CDR chain.	unitless
$mCO_{2eq,p,emboddied,y}$	=	Embodied GHG emissions due to construction and disposal of phase (p) facilities as scheduled for monitoring period (y)	tonne (tCO_2)

Where			
$I_{electricity,capture,y}$	=	Operational Electricity used in capture, in period (y)	MWh
$ef_{electricity,capture,y}$	=	Emission factor of electricity used	tCO_2/MWh
$I_{heat,capture,y}$	=	Operational heat used during capture, in period (y)	MWh
$ef_{heat,capture,y}$	=	Emissions factor for heat use	tCO_2/MWh
$I_{sorbent,capture,y}$	=	Quantity sorbent used to operate capture, in period (y).	tonne (t/y)
$ef_{sorbent,capture,y}$	=	Emissions factor for sorbent	tCO_2/ $t_{sorbent}$
$I_{other\ process\ input,capture,y}$	=	Quantity water used to operate capture, in period (y).	tonne (t_{water})
$ef_{other\ process\ input,capture,y}$	=	Emissions factor for water	tCO_2/ t_{water}
$I_{electricity,storage,y}$	=	Operational Electricity used in storage, in period (y)	MWh
$ef_{electricity,storage,y}$	=	Emission factor of electricity used	tCO_2/MWh

Attachment C – Monitoring Plan

climeworks

Basic Information	
Project name	Orca
Date of Version	26.02.2024
Project Proponent(s)	Climeworks AG
Project Operator(s)	Climeworks AG, Carbfix hf
MRV cycle	1
Certifying body	Puro
Prepared by	Climeworks AG Birchstrasse 155 CH - 8050 Zurich +41 (0)44 533 29 99 contact@climeworks.com
Aknowledgement	To the best of our knowledge, this presents the world's first certification of a Direct Air Capture and Storage project ever. This milestone wouldn't have been achievable without extensive collaboration between Carbfix and Climeworks. Whilst Climeworks is the sole project proponent listed, we are grateful and proud to have achieved this milestone together with Carbfix. Carbfix

1. Monitoring Plan

The monitoring plan developed for Project Orca is provided as a supplementary material and provides data to inform:

1. Emission accounting which includes:
    - Project emissions
    - Quantification of the CO_2 injected at the storage site
    - Detection of intentional or unintentional release of CO_2 from the injection system and the geological storage reservoir. In case of detection, corrective measures must be applied, and the amount of CO_2 released must be quantified.
2. Full dissolution of CO_2 is achieved prior to entering the geological storage reservoir (solubility trapping)
3. The permanent storage of the CO_2 (in-situ carbon mineralization).

Table 1: Responsible Persons for Collecting and Archiving

Name **Area/ Dept.**	**Data Source** **Monitoring freq.**	**Brief Description**
Climeworks: Director Plant Operations	Internal control spread-sheet Monthly	Oversees overall project emissions and the amount of CO_2 transferred to the transport pool
Climeworks: MRV Manager	Internal control spread-sheet Monthly	Oversees overall project emissions and the amount of CO_2 transferred to the transport pool
Climeworks: Director Sales Operation	Internal control sales registry Monthly	Oversees all CDR transactions and allocates the CDR realized by Orca to a specific customer
Carbfix: Head of MRV	Internal control system and spreadsheets Monthly	Oversees the monitoring of the amount of CO_2 injected and other relevant parameters
Carbfix: Technical expert	Internal control system and spreadsheets Monthly	Oversees the monitoring of the amount of CO_2 injected and other relevant parameters

CO_2 credited during monitoring period

$$mCO_{2,credited,y} = mCO_{2,\text{injected},y} - mCO_{2,\text{released},y} - mCO_{2eq,\text{project},\text{operation},y} - mCO_{2eq,\text{project},\text{embodied},y}$$

Calculation of CO_2 credited during monitoring period (y): Equation. 1

Parameter	$mCO_{2,credited,y}$
Parameter Type	calculated
Data unit	tonne (tCO_2)
Description	Total amount of CO_2 credited in own accounting or sold/transacted to third parties in monitoring period y.
Equations	Equation 1
Source of data	NA
Calculation method/equations	Equation 1
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of Data	CDR Credited
Comments	

Parameter	$mCO_{2,\text{injected},y}$
Parameter Type	calculated
Data unit	tonne (tCO_2)
Description	Total amount of CO_2 injected in the geological storage in monitoring period y, determined at the last monitoring point on the injection system.
Equations	Equation 1 Equation 2/2.a
Source of data	NA
Calculation method/equations	Equation 2
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of Data	CDR Credited
Comments	

Parameter	$mCO_{2,\text{released},y}$
Parameter Type	calculated
Data unit	tonne (tCO_2)
Description	Total amount of CO_2 released downstream of the last monitoring point at the storage site in monitoring period y.
Equations	Equation 1 Equation 4
Source of data	calculated
Calculation method/equations	Equation 3
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of Data	CDR Credited
Comments	

Parameter	$mCO_{2eq,\text{project},\text{operation},y}$
Parameter Type	calculated
Data unit	tonne (tCO_2)
Description	total GHG emissions due to project operations of the CDR value chain (DAC, transport, and storage) in monitoring period y.
Equations	Equation 1 Equation 5/ 5.a
Source of data	NA
Calculation method/equations	Equation 4
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of Data	CDR Credited
Comments	

Parameter	$mCO_{2eq,\text{project,embodied},y}$
Parameter Type	calculated
Data unit	tonne (tCO_2)
Description	total GHG emissions due to construction and disposal of the CDR value chain (DAC, transport, and storage) scheduled for monitoring period y.
Equations	Equation 1 Equation 6
Source of data	NA
Calculation method/equations	Equation 5
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The minimal period of i) every audit or ii) yearly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of Data	CDR Credited
Comments	

1.1 CO_2 injected during monitoring period

$$mCO_{2,injected,y} = \int_0^y \dot{m}_{CO2} \cdot (x_{CO2})dt$$

Simplified Calculation of Total CO_2 injected during monitoring period: Equation. 2.a

Parameter	$\dot{m}_{CO2}$
Parameter Type	measured
Data unit	tonne/sec (t/s)
Description	The mass flow rate of the CO_2 stream at the injection well.
Equations	Equation 2.a Equation 3 Equation 8 ($P_{\text{Bubble point}}$ input)
Source of data	On-site measurement
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Measurements will be made using a coriolis mass flow meter (Endress+Hauser Proline Promass E100, ±0.5% uncertainty, >1 measurement per minute) installed on the injection system. 10-minute or higher-frequency averages are stored in the database every minute.
Frequency of monitoring	Monthly
QA/QC procedures to be applied	Annual recalibration starting from the first monitoring period.
Justification of choice of data source	continuous metering at the injection point ensures accuracy void of any release quantities
Purpose of Data	CO_2 injection
Comments	NA

Parameter	x_{CO2}
Parameter Type	fixed
Data unit	W_{CO2}/ W_{stream} (unitless)
Description	The CO_2 weight fraction of the CO_2 stream entering the injection well
Equations	Equation 2.a Equation 3
Source of data	Manufacturer specification of the liquefaction unit at the capture site generating the CO_2 stream entering the injection well.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	Fixed value, confirmed twice a year
QA/QC procedures to be applied	Samples will be analyzed at accredited laboratory twice a year.
Justification of choice of data source	In project Orca, the CO_2 stream entering the injection well will generated from a liquefaction unit. Such units are also used in the beverage industry, where industry practice trusts the production of high liquid purity CO_2. Because of the physics of liquefaction, the resulting CO_2 stream will be of high purity (99.99%). Purity will be confirmed biannually through sampling and laboratory testing. Due to its high purity, it is difficult to continuously measure the CO_2 to the precision required to provide accurate data. This is because of the technical limitations of analytical equipment. This CO_2 streams will remain pressurized in a single stream from liquefaction to injection, eliminating any physical chance for impurities to mix with the stream without changing pressure readings. Therefore, the composition of the CO_2 stream will be considered constant from liquefaction to injection.
Purpose of Data	CO_2 injection
Comments	

1.2 CO_2 Released During Release Events

$$mCO_{2,released,y} = \sum_j mCO_{2,\,release\ event,injection\ system,j} + \sum_k mCO_{2,\,release\ event,geological\ storage,k}$$

Calculation of total CO_2 Released During Release Events: Equation. 4

Parameter	$mCO_{2,\,release\ event,injection\ system,j}$
Parameter Type	measured
Data unit	tonne (tCO_2)
Description	Mass of CO_2 released intentionally or unintentionally from the injection system downstream of the last monitoring point on the injection system during event j
Equations	Equation 4
Source of data	Quantification based on type of event.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	A CO_2 sensor (Crowcon Xgard Bright) is installed at the injection wellhead to detect any unintentional release of CO_2. If any unintentional release is detected, it will be quantified based on type of event. For any occasion of $P_{\text{BubblePoint}}$ exceeding its limits, the mass of CO_2 injected while this conditions persists will be attributed to this parameter as conservative estimate.
Frequency of monitoring	Monthly
QA/QC procedures to be applied	Annual recalibration of the CO_2 sensor installed at the wellhead starting from the first monitoring period.
Justification of choice of data source	NA
Purpose of Data	CO_2 release
Comments	

Parameter	$mCO_{2,\,release\,event,geological\,storage,k}$
Parameter Type	measured
Data unit	tonne (tCO_2)
Description	Mass of CO_2 released intentionally or unintentionally from the geological storage reservoir during event k.
Equations	Equation 4
Source of data	Quantification based on type of event.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	If any release is detected or planned, it will be quantified based on type of event. Individual CO_2 surface flux measurement campaigns will be carried out around the injection site according to monitoring plan. Any monitoring well producing significant volumes of water will be fitted with a CO_2 sensor at its wellhead.
Frequency of monitoring	Annually
QA/QC procedures to be applied	The CO_2 surface flux meter will be maintained and recalibrated according to the manufacturer specifications. Annual recalibration of any CO_2 sensors installed at monitoring wellheads.
Justification of choice of data source	Justification to be made in monitoring report according to event characteristics
Purpose of Data	CO_2 release
Comments	

1.3 GHG Emissions from Project Operation

$$mCO_{2eq,project,operation,y} = [(I_{electricity,capture,y} \cdot ef_{electricity,capture,y}) + (I_{heat,capture,y} \cdot ef_{heat,capture,y}) + (I_{sorbent,capture,y} \cdot ef_{sorbent,capture,y}) + (I_{other\ process\ input,capture,y} \cdot ef_{other\ process\ input,capture,y})]_{capture} + [(I_{electricity,storage,y} \cdot ef_{electricity,storage,y})]_{storage}$$

GHG Emissions from Project Operation: Equation. 5.a

Parameter	$I_{electricity,capture,y}$
Parameter Type	measured
Data unit	MWh
Description	Total electricity usage from equipment used to operate the CO_2 capture and post-capture treatment facilities.
Equations	Equation 5.a
Source of data	Values provided by the electricity supplier in monthly invoices
Description of measurement methods and procedures to be applied	Electricity consumption is determined by continuous measurement in Landis+Gyr E650 meters operated by the electricity supplier ON Power.
Frequency of monitoring	Monthly (invoices supplied by electricity provider ON Power)
QA/QC procedures to be applied	Electricity meters are maintained according to national standards.
Justification of choice of data source	NA
Purpose of Data	Operational emissions
Comments	

Parameter	$ef_{electricity,capture,y}$
Parameter Type	fixed
Data unit	tCO_2/MWh
Description	Emission factor for electricity generation.
Equations	Equation 5.a
Source of data	Assessment by electricity provider ON Power.
Description of measurement methods and procedures to be applied	Value determined from LCA conducted for the power plant (Karlsdottir, 2020)
Frequency of monitoring	The CO_2 emission factor will be obtained from monthly invoices and revised accordingly
QA/QC procedures to be applied	NA
Justification of choice of data source	Assessment conducted following ISO 14040/14044 LCA methodology
Purpose of Data	Operational emissions
Comments	

Parameter	$I_{heat,capture,y}$
Parameter Type	measured
Data unit	MWh
Description	Total metered heat usage from equipment used to operate the CO_2 capture and post-capture treatment facilities, supplied by ON Power, in monitoring period y.
Equations	Equation 5.a
Source of data	Values provided by the electricity supplier in monthly invoices
Description of measurement methods and procedures to be applied	Thermal energy consumption is determined by ON Power using kamstrup MultiCAL 803 calculator and stated in monthly invoices
Frequency of monitoring	Monthly
QA/QC procedures to be applied	Metered and equipment maintained according to national standards.
Justification of choice of data source	NA
Purpose of Data	Operational emissions
Comments	

Parameter	$ef_{heat,capture,y}$
Parameter Type	fixed
Data unit	tCO_2/MWh
Description	Emission factor for heat generation supplied by ON Power.
Equations	Equation 5.a
Source of data	Assessment by heat provider ON Power.
Description of measurement methods and procedures to be applied	Value determined from LCA conducted for the power plant (Karlsdottir, 2020)
Frequency of monitoring	The CO_2 emission factor will be obtained from monthly invoices
QA/QC procedures to be applied	NA
Justification of choice of data source	Assessment conducted following ISO 14040/14044 LCA methodology
Purpose of Data	Operational emissions
Comments	

Parameter	$I_{sorbent,capture,y}$
Parameter Type	measured
Data unit	tonne (t/y)
Description	Total sorbent material usage used to operate the CO_2 capture and post-capture treatment facilities, in monitoring period y.
Equations	Equation 5.a
Source of data	On-site measurement
Description of measurement methods and procedures to be applied	Dry mass of sorbent (re)filled into plant will be measured and tracked upon every sorbent replacement. Based on accumulated operations experience, an average sorbent consumption rate is calculated ($t_{sorbent}/t_{CO2\ captured}$) and multiplied by the mass of CO_2 captured to determine the sorbent mass to report for the monitoring period. Ex-ante estimates of average sorbent consumption rate will be updated as needed to ensure all used sorbent is accounted for.
Frequency of monitoring	Upon initial filling, refilling, and every sorbent replacement thereafter.
QA/QC procedures to be applied	scales maintained according to manufacturer's standards
Justification of choice of data source	NA
Purpose of Data	Operational emissions
Comments	

Parameter	$ef_{sorbent,capture,y}$
Parameter Type	fixed
Data unit	$tCO_2/\ t_{sorbent}$
Description	Emission factor of the sorbent material, in monitoring period y.
Equations	Equation 5.a
Source of data	Contracted LCA by an independent laboratory
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	Prior to initial filling and subsequently by the minimal period of either every second sorbent replacement process, or annually.
QA/QC procedures to be applied	NA
Justification of choice of data source	Assessment conducted following ISO 14040/14044 LCA methodology
Purpose of Data	Operational emissions
Comments	

Parameter	$I_{other\ process\ input,capture,y}$
Parameter Type	measured
Data unit	tonne (t_{water})
Description	Total metered water usage from equipment used to operate the CO_2 capture and post-capture treatment facilities, in monitoring period y
Equations	Equation 5.a
Source of data	Assessment by water provider ON Power.
Description of measurement methods and procedures to be applied	Water consumption is determined by continuous measurement in a Kamstrup Multical 803 meter operated by the water suppliers ON Power.
Frequency of monitoring	Monthly (invoices or reports supplied by water provider ON Power)
QA/QC procedures to be applied	Water meter is maintained according to national standards.
Justification of choice of data source	NA
Purpose of Data	Operational emissions
Comments	

Parameter	$ef_{other\ process\ input,capture,y}$
Parameter Type	fixed
Data unit	$tCO_2/\ t_{water}$
Description	Emission factor of the water used for cooling supplied by ON Power.
Equations	Equation 5.a
Source of data	Assessment by water provider ON Power.
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The CO_2 emission factor will be obtained from monthly invoices and revised accordingly
QA/QC procedures to be applied	NA
Justification of choice of data source	Assessment conducted following ISO 14040/14044 LCA methodology
Purpose of Data	Operational emissions
Comments	

Parameter	$I_{electricity,storage,y}$
Parameter Type	measured
Data unit	MWh
Description	Total electricity usage from equipment used to operate the CO_2 storage.
Equations	Equation 5.a
Source of data	On-site measurement
Description of measurement methods and procedures to be applied	Electricity consumption is determined by continuous measurement in Iskrameco meters operated by the electricity supplier ON Power.
Frequency of monitoring	Monthly (invoices supplied by electricity provider ON Power)
QA/QC procedures to be applied	Electricity meters are maintained according to national standards.
Justification of choice of data source	NA
Purpose of Data	Operational emissions
Comments	

Parameter	$ef_{electricity,storage,y}$
Parameter Type	fixed
Data unit	tCO_2/MWh
Description	Emission factor for electricity generation.
Equations	Equation 5.a
Source of data	Value determined from LCA conducted for the power plant (Karlsdottir, 2020)
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	The CO_2 emission factor will be obtained from monthly invoices and revised accordingly
QA/QC procedures to be applied	NA
Justification of choice of data source	Assessment conducted following ISO 14040/14044 LCA methodology
Purpose of Data	Operational emissions
Comments	

1.4 GHG Embodied Emissions from Construction and Disposal

$$mCO_{2eq,\text{project,embodied},y} = \sum_{p} mCO_{2eq,p,embodied,y}$$

PDD Equation. 6

Parameter	$mCO_{2eq,capture,emboddied,y}$
Parameter Type	fixed
Data unit	tonne (tCO_2)
Description	Emissions due to construction and disposal for the capture phase during the monitoring period y.
Equations	Equation 6
Source of data	LCA from Bardow and Deutz (2021) adjusted to reflect actual consumption rates
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	determined ex ante
QA/QC procedures to be applied	NA
Justification of choice of data source	values according to academic LCA from Bardow and Deutz (2021). Total embodied emissions scheduled to be deducted in project years 3-10 as outlined in the PDD.
Purpose of Data	Embodied emissions
Comments	

Parameter	$mCO_{2eq,transport,emboddied,y}$
Parameter Type	fixed
Data unit	tonne (tCO_2)
Description	Emissions due to construction and disposal for transport and storage during the monitoring period y.
Equations	Equation 6
Source of data	LCA conducted by KPMG following ISO 14040/14044 guidelines.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	determined ex ante
QA/QC procedures to be applied	NA
Justification of choice of data source	values according to pending LCA for transport and storage. Total embodied emissions scheduled to be deducted in project years 3-10 as outlined in the PDD.
Purpose of Data	Embodied emissions
Comments	

Parameter	$mCO_{2eq\,storage,emboddied,y}$
Parameter Type	fixed
Data unit	tonne (tCO_2)
Description	Emissions due to construction and disposal for transport and storage during the monitoring.
Equations	Equation 6
Source of data	LCA conducted by KPMG following ISO 14040/14044 guidelines.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	determined ex ante
QA/QC procedures to be applied	NA
Justification of choice of data source	values according to pending LCA for transport and storage. Total embodied emissions scheduled to be deducted in project years 3-10 as outlined in the PDD.
Purpose of Data	Embodied emissions
Comments	

1.5 Dissolution of the Gaseous CO_2 and Solubility Trapping

$$P_{reservoir} > P_{\text{BubblePoint},i} + P_{margin}$$

Equation. 7

Parameter	$P_{reservoir}$
Parameter Type	fixed
Data unit	bar-a
Description	Pressure at the bottom of the casing of injection well i.
Equations	Equation 7
Source of data	Water table was determined on 30.04.2021 using a video camera recording the water table location at 91.5 m. From this, reservoir (hydrostatic) pressure is calculated using the well casing depth of 400m as (400m-91.5m)*9.81m/s2 * 1000 kg/m3 = 30.26 bar. Adding the atmospheric pressure of 1.01 bar, the absolute pressure is 31.27 bar-a.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	The water table depth measurement by video camera is the most accurate and recent source of data.
Purpose of Data	CO_2 release
Comments	

Parameter	$P_{\text{BubblePoint}}$
Parameter Type	calculated
Data unit	bar-a
Description	Pressure where the first bubble of gas (including CO_2) is formed when depressurizing the liquid injected at injection well.
Equations	Equation 7 Equation 8
Source of data	NA
Calculation method/equations	$P_{\text{BubblePoint}}$ is solved using the PHREEQC software version 3 as a function of parameters listed in Equation 8. The software solves for the pressure of the system when an infinitesimally small volume of gas is formed from the injected water-gas mixture.
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	Monthly
QA/QC procedures to be applied	NA
Justification of choice of data source	NA
Purpose of Data	CO_2 release
Comments	

Parameter	P_{margin}
Parameter Type	fixed
Data unit	bar-a
Description	Pressure safety margin
Equations	Equation 7
Source of data	Operational experience
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	Determined through operational experience.
Purpose of Data	CO_2 release
Comments	

$$P_{\text{BubblePoint}} = f(\dot{m}_{CO2}, \ \dot{m}_{water,i}, \ T_{water}, \ T_{CO2}, \ Elem_{CO2}, \ Elem_{water})$$

Equation. 8

Parameter	$\dot{m}_{water}$
Parameter Type	measured
Data unit	kg/s
Description	Mass flow rate of the water stream entering the injection well.
Equations	Equation 8
Source of data	On-site measurement
Calculation method/equations	NA
Description of measurement methods and procedures applied	Electromagnetic flow meter (Endress+Hauser Proline Promag P100, ±0.5% uncertainty, >1 measurement per minute). 10-minute or higher-frequency averages are stored in the database every minute. Volume flow rates are converted to mass flow rates using a density of 1000 kg/m3.
Frequency of monitoring	At audit
QA/QC procedures applied	Annual recalibration date had not passed at time of audit.
Justification of choice of data source	NA
Purpose of Data	CO_2 injection
Comments	

Parameter	T_{water}
Parameter Type	measured
Data unit	$°C$
Description	Temperature of the water stream entering the injection well.
Equations	Equation 8
Source of data	On-site measurement
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	The temperature of the water entering the injection system will be continuously measured using a resistance temperature detector (Endress+Hauser iTHERM ModuLine TM131, >1 measurement per minute). 10-minute or higher-frequency averages are stored in the database every minute.
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	Annual recalibration starting from the first monitoring period
Justification of choice of data source	NA
Purpose of Data	CO_2 injection
Comments	

Parameter	T_{CO2}
Parameter Type	fixed
Data unit	*°C*
Description	Temperature of the CO_2 stream entering the injection well.
Equations	Equation 8
Source of data	Fixed value based on the average temperature during CO_2 injection in the first monitoring period of project Orca.
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	NA
Frequency of monitoring	NA
QA/QC procedures to be applied	NA
Justification of choice of data source	Previous measurements have shown variation is negligible and the impact this variable has on the bubble point is negligible.
Purpose of Data	CO_2 injection
Comments	

Parameter	$Elem_{CO2}$
Parameter Type	measured
Data unit	*Vol% (for gas streams)* *mg/kg (for liquid streams)*
Description	Elemental composition of the CO_2 stream entering the injection well.
Equations	Equation 8
Source of data	On-site sampling in the injection system and off-site laboratory analysis
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Sampling twice a year and laboratory analysis by standard techniques, such as Gas Chromatography (GC).
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	GC will be calibrated by running recognized standards before, during and after sample analysis.
Justification of choice of data source	NA
Purpose of Data	CO_2 injection
Comments	

Parameter	$Elem_{water}$
Parameter Type	measured
Data unit	*mg/kg*
Description	Elemental composition of the water stream entering the injection well.
Equations	Equation 8
Source of data	On-site sampling in the injection system and on-site analysis of pH and off-site laboratory analysis for other elements
Calculation method/equations	NA
Description of measurement methods and procedures to be applied	Annual sampling and analysis by standard techniques, such as pH combination electrodes, inductively coupled optical emission spectrometry (ICP-OES), and ion chromatography (IC).
Frequency of monitoring	The minimal period of i) every audit or ii) yearly.
QA/QC procedures to be applied	pH electrodes will be calibrated every time before use using manufacturer's reference materials and ICP-OES/IC will be calibrated by running recognized standards before, during and after sample analysis.
Justification of choice of data source	NA
Purpose of Data	CO_2 injection
Comments	0

Monitoring of Mineral Storage

1.6 Site characterization

Project Orca uses the same storage site and installations as were used for the demonstration of the Carbfix technology between 2011 and 2012 demonstrating the site's viability for carbon storage. A pilot injection was carried out in which 175 tonnes of CO_2 was injected at the storage site. The CO_2 was fully dissolved in water and the CO_2-charged fluid was released into the basaltic rocks at depths greater than 450 m.

- The storage site is located in SW-Iceland on the western flank of the Hengill central volcano. The site is characterized by basaltic lavas and volcanic formations formed during glacial periods. The storage formation consists of sequence of fresh and porous basaltic lavas. The permeability is mostly present on boundaries between lava flows, but also in younger fractures and faults (Alfredsson et al., 2013; Snæbjörnsdóttir et al., 2018).
- The in-situ carbon mineralization process was demonstrated and quantified using reactive and non-reactive tracers and isotopes to reveal the over 95% of the injected gas was rapidly mineralized within two years (Matter et al., 2016 and Pogge von Strandmann et al., 2019).
- Predictive reactive transport simulations for both a 1200-tonnes pilot CO_2 injection and a full-scale 400,000-tonnes CO_2 injection scenario show that the injected CO_2-charged water is capable of leaching cations from the basaltic rock matrix. This eventually results in the pore water becoming super-saturated with respect to carbonates, indicating conditions favorable for carbon mineralization.
- Reactive transport simulations of the pilot injection predict 100% mineralization of injected CO_2 within 10 years and cumulative fixation per unit surface area of 5000 tonnes/km2. Corresponding values for the full-scale scenario are 80% CO_2 mineral capture after 100 years and cumulative fixation of 35,000 tonnes/km2. CO_2 sequestration rate is predicted to range between 1200 and 22,000 tonnes/year in both scenarios (Aradóttir et al., 2012).

Main findings applicable to in-situ mineralization in Project Orca:

- Complete dissolution of CO_2 gas was confirmed within the injection well with solubility trapping achieved within 5 minutes from the mixing of the down going CO_2 and water streams (the residence time in mixing pipe to sampling with downhole bailer) (Sigfússon et al., 2015).
- The storage site of Project Orca is suitable for mineral storage of CO_2. The storage reservoir consists of fresh basaltic lavas that react rapidly when exposed to the acidic CO_2 charged fluid, releasing cations for the mineralization process (Snæbjörnsdóttir et al., 2017)
- In-situ carbon mineralization has been demonstrated for conditions within the geological storage reservoir with super-saturation of the formation fluids with respect to carbonate minerals (Snæbjörnsdóttir et al., 2017), and loss of CO_2 along the flow-path path as demonstrated by tracer tests using reactive and non-reactive tracers (Matter et al., 2016).

Additional findings applicable to in-situ mineralization in Project Orca:

- Models predicting the minimum downward flowing velocity of water to prevent the uprising of CO_2 gas bubbles were calibrated enabling better design of injection wells and optimum reinjection parameters.
- Geochemical methods can effectively be used to quantify the mineralization process. Two independent approaches reveal the rapid mineralization of the injected CO_2.

- An extensive monitoring campaign of downstream water chemistry provided a guideline for suitable sampling frequencies in monitoring wells and a reference for monitoring well locations.

1.7 During operation

Different parameters and conditions are monitored throughout Project Orca to ensure safe operation, accurate quantification of CO_2 stored, and permanence of stored CO_2. The following discusses the monitoring plan (provided in supplementary documentation) and procedures in place for Project Orca. The general concepts are illustrated in Figure 1.

The subsurface monitoring system includes:

- Monitoring of the CO_2 Injection
  - Mass flow, pressure, and temperature of the gas injection
  - Mass flow, pressure, and temperature of the water injection
  - Elemental composition of the CO_2 stream and water supply
  - CO_2 gas detector in Ground Control and wellhead building.
- Monitoring of the geological CO_2 storage reservoir
  - Monitoring wells: The storage reservoir is monitored through geochemical sampling of the reservoir fluids from monitoring wells located downstream the injection well. There are a total of four monitoring wells for Project Orca: Wells HN-04, HK-34, HK-31 and HK-26. Wells HN-04 and HK-34 are located about 70 m and 300 m, respectively, downstream from the injection well, HN-02 at reservoir depths. Wells HK-31 and HK-26 are located 1750 m and 3000 m downstream from well HN-02, respectively, on the boundary of the storage site.

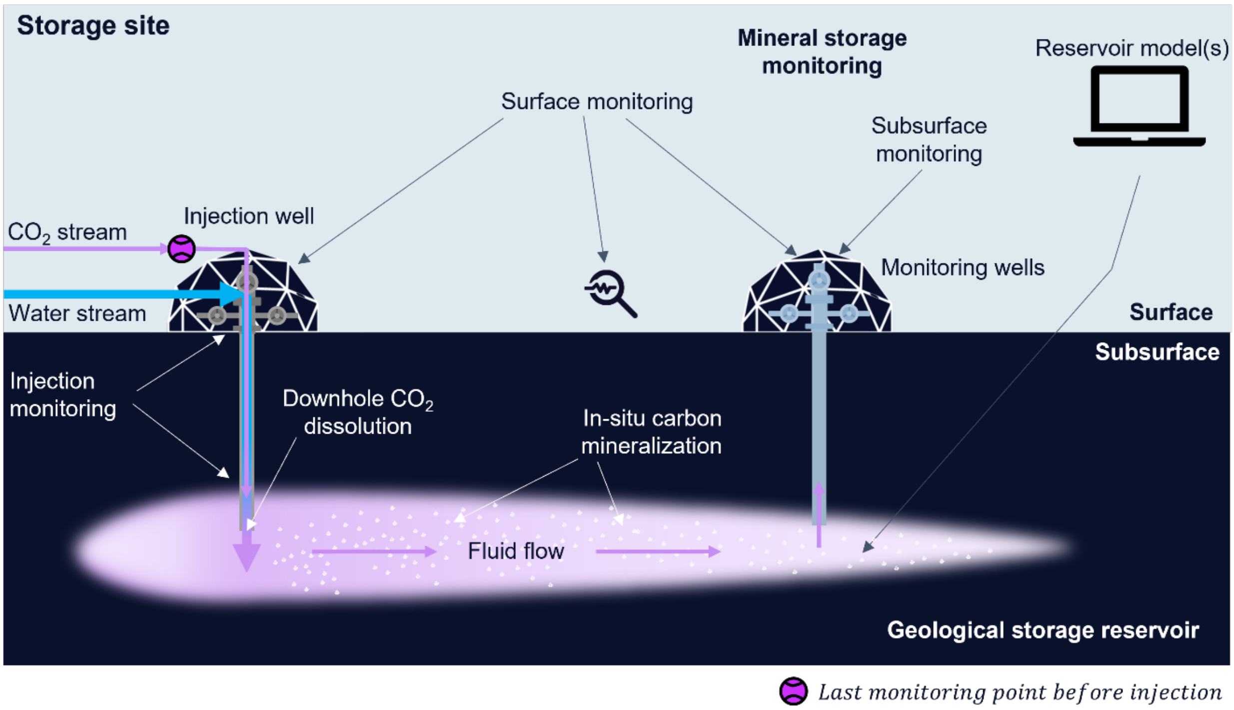


Figure 1: Injection system and geological storage reservoir. The injected CO_2-charged fluids enter the subsurface and flow through and interact with the reservoir bedrock. The subsurface fluids are

sampled via monitoring wells to monitor the geochemical processes taking place within the reservoir and verify the mineralization of the injected CO_2.

1.7.1 Monitoring of the CO_2 Injection

1.7.1.1 Full dissolution of CO_2 in the injection well is ensured by wellhead measurements that can detect unexpected changes of the water mass flow with sufficient accuracy and frequency to allow for the detection of gas bubble ascent in the well.

• Purpose of monitoring
  ○ Satisfy conditions for solubility trapping
  ○ Ensure safe injection

• Parameter monitored
  ○ Mass flow and pressure of the gas injection
  ○ Mass flow and pressure of the water injection

• Procedure if threshold is exceeded   ○ Modify injection operations

1.7.1.2 Sufficient reservoir pressure to maintain the CO_2 in solution (solubility trapping) is ensured by comparison with the bubble point pressure ($P_{BubblePoint,i}$) of the injected water and CO_2 mixture. This ensure that solubility trapping condition is satisfied, and that CO_2 does not degas, which would potentially lead to release towards the surface. To ensure these conditions, the pressure of the reservoir must be greater than the bubble point (the pressure at which the CO_2 will degas out of solution) plus a pressure buffer. This concept is displayed in Equation 7.

$$P_{reservoir} > P_{\mathrm{BubblePoint},i} + P_{margin}$$

Ensuring Solubility trapping of CO_2 in water Equation. 7

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 7

where

$$P_{\mathrm{BubblePoint}} = f(\dot{m}_{CO2}, \dot{m}_{water}, T_{water}, T_{CO2}, Elem_{CO2}, Elem_{water})$$

Determining Bubble Point Equation. 8

Permanent and Secure Geological Storage of CO_2 by In-Situ Carbon Mineralization Equation 7

$P_{reservoir}$	=	is the pressure at the bottom of the well casing	bar-a
$P_{\mathrm{BubblePoint}}$	=	Pressure where the first bubble of gas (including CO_2) is formed when depressurizing the liquid injected at injection point	bar-a
P_{margin}	=	pressure safety margin	bar-a
f	=	Applicable Equation of State	bar-a
$\dot{m}_{CO2}$	=	The mass flow rate of the CO_2 stream at the injection well, metered continuously	tonne/sec (t/s)
$\dot{m}_{water}$	=	Mass flow rate of the water stream entering the injection well	kg/s
T_{water}	=	Temperature of the water stream entering the injection well	°C
T_{CO2}	=	Temperature of the gas stream entering the injection well	°C
$Elem_{CO2}$	=	Elemental composition of the gas stream entering the injection well	Vol%
$Elem_{water}$	=	Elemental composition of the water stream entering the injection well	mg/kg

$P_{\mathrm{BubblePoint},i}$ is calculated using the Peng-Robinson equation of state for the solubility of gases and other thermodynamic data for aqueous and gas species in the *carbfix.dat* thermodynamic database (Voigt et al., 2018). Specifically, the bubble point is calculated using the PHREEQC software version 3 as the pressure of the system when an infinitesimally small volume of gas is formed from the mixture of the injected water and gas.

• Purpose of monitoring ○ Ensures solubility trapping and absence of CO_2 release from the reservoir ○ Ensures conditions are optimal for in-situ carbon mineralization
• Parameters monitored and threshold maintained ○ Mass flow and temperature of the gas injection ○ Mass flow and temperature of the water injection • Composition of the CO_2 stream and water supply
• Procedure if threshold is exceeded ○ Amount of injected CO_2 during events in which the bubble point pressure exceeds the reservoir pressure (with a 5 bara buffer) is recorded as a CO_2 release event.

5.2.1.3 Detection of unexpected CO_2 release is ensured by CO_2 sensors that detect CO_2 accumulation in the wellhead building and the Orca Hut is recorded.

• Purpose of monitoring ○ Detect any CO_2 leakage from the wellhead for permanence concerns ○ Personnel safety
• Parameters monitored ○ Ambient CO_2 levels
• Procedure if threshold is exceeded ○ Identification of the cause of the CO_2 release and quantification of the amount of CO_2 released during the event, and/or ○ Modify injection operations

1.7.2 Monitoring of the geological CO_2 storage reservoir

Field sampling and reservoir models are used together to provide estimates of the degree of mineralization in the storage reservoir. This includes:

5.2.2.1 Tracer test and tracer sampling of monitoring wells

• Purpose of monitoring ○ Monitor the migration of the injected CO_2 ○ Estimate the degree of CO_2 mineralization ○ Mass balance equation (if applicable) ○ Input for numerical model(s)
• Parameters monitored ○ tracer concentration (mg/kg)
• Procedure if threshold is exceeded ○ Update numerical models and ○ Update monitoring program, and/or ○ Modify injection operations

5.2.2.2 Chemical sampling of monitoring wells

• Purpose of monitoring
  ○ Monitor the migration of the injected CO_2,
  ○ Estimate the degree of CO_2 mineralization,
  ○ Calculation of the fluid saturation state, and
  ○ Input for numerical model(s).

• Parameters monitored   ○ Si, Ca, Mg, Fe, Al, Na, K, S, Cl, C (dissolved inorganic carbon, DIC), and O_2 concentration (mg/kg).

• Procedure if threshold is exceeded
  ○ Update numerical models and
  ○ Update monitoring program, and/or
  ○ Modify injection operations.

5.2.2.3 Numerical model

• Purpose of monitoring
  ○ Monitor the migration of the injected CO_2
  ○ Estimate the degree of CO_2 mineralization.

• Parameters monitored
  ○ Percentage of the injected CO_2 contained by solubility trapping.
  ○ Percentage of the injected CO_2 contained by mineral trapping.

• Procedure if threshold is exceeded   ○ Modify injection operations, quantify potential amount of CO_2 released from the storage complex, update monitoring plan, and/or stop injection operations.

5.2.2.3 Surface flux measurement

• Purpose of monitoring
  ○ Monitor the migration of the injected CO_2.
  ○ Estimate the degree of CO_2 mineralization
  ○ Calculation of the fluid saturation state
  ○ Input for numerical model(s)

• Parameters monitored   ○ Surface CO_2 mass flux (g/m^2/day)

• Procedure if threshold is exceeded
  ○ Identification of the cause of the CO_2 release and quantification of the amount of CO_2 released during the event.
  ○ Update numerical models and
  ○ Update monitoring program, and/or
  ○ Modify injection operations

1.8 Closure and post closure

The closure and post closure monitoring plan is provided in supplementary documentation.

It includes:

1.8.1 Tracer sampling of monitoring wells to inform:

- The behavior of the CO_2 has trended towards increased conformance with modelled predictions

1.8.2 Chemical sampling of monitoring wells.

- The behavior of the CO_2 has trended towards increased conformance with modelled predictions

1.8.3 Annual update to the reservoir model(s) to inform:

- The dissolved CO_2 spatial extent and associated pressure front.
- Reservoir pressures in compliance with Equation 8.
- The amount of CO_2 mineralized.
- The CO_2 has trended towards a situation of increased long-term stability.

1.8.4 Surface flux measurements

- No evidence for CO_2 released from the geological storage complex

Carbfix Silverstone Project
(expanded injection at Hellisheiði including Orca Project)

Stakeholder Engagement part of the **"Knowledge Sharing Report"**
submitted to the **EU Innovation Fund**, June 2023

Compiled here by Carbfix for purposes of Orca audit/certification under the Puro.earth standard

D1.5 Stakeholder engagement, including public communication strategies

Communication objectives

Communication objectives were to inform stakeholders of the nature of the project and its implications. Methods included:

a) Website with overview of the project:(www.carbfix.com/project-silverstone)
b) Website featuring detailed information on the Environmental Impact Assessment report and an extensive Q&A section on the project. (www.carbfix.com/is/silfurberg)
c) Press releases and media outreach related to project milestones.
d) Open meeting to present the Environmental Impact Assessment (EIA) with opportunity for Q&A.
e) Information posters on display at Reykjavík Energy and Carbfix headquarters.
f) Meetings with selected stakeholders including officials at the municipalities of Hveragerði and Ölfus.

Target groups selected and number of stakeholders reached

Stakeholders defined and engaged included:

- The general public
- Municipal authorities including Ölfus, Hveragerði and Reykjavík
- Commercial partners such as Reykjavík Energy, ON Power and Climeworks
- Internal stakeholders at Carbfix (employees and board)
- Domestic media
- National and municipal regulators and licensing authorities
- The national government (ministries)
- International authorities relevant to licensing and legal framework (EFTA Surveillance Authority)
- Environmental associations and other NGO's
- Landowners at the site.

All of these were engaged.

Methods of communication

The main methods of communication employed are outlined above ("Communication objectives"). In addition, the legal process for the project's EIA provided a formal avenue for any and all stakeholders to submit comments on the report, voicing their concerns, which the company in turn addressed and responded to. Carbfix has also participated in international conferences to share its approach and learnings with international stakeholders such as academia, industries, NGO's and regulators.

Timing/frequency of stakeholder engagement

The project was introduced at meetings with the National Planning Agency in November 2021, the municipality of Ölfus in December 2021, the Environmental Agency in December 2021, the municipality of Hveragerði in January 2022, and several municipal health committees in February 2022.

Prior to this the project had been introduced to numerous stakeholders in relation to the preparation of national legislation on carbon storage.

Stakeholder visits to Carbfix's operations at Hellisheiði include the environmental associations Landvernd and Náttúruverndarsamtök Íslands (March 2021); the Ministry of Environment and the Foreign Ministry, the National Planning Agency and the Environmental Agency (May 2021); and environmental association Ungir umhverfissinnar (October 2021).

Further visits to the site include government ministers, members of Parliament, municipal health officials and the EFTA Surveillance Authority.

In June 2022 Carbfix [and Climeworks] visited the municipalities of Ölfus and Hveragerði as well as Landvernd to discuss related plans for direct air capture at Hellisheiði.

The EIA provided for stakeholder input at various stages in both 2022 and 2023. Carbfix also held an open meeting to present the EIA in February of 2023.

National and municipal regulators were continuously updated at ON Power's bi-monthly meetings with regulators and licensing authorities. The media was engaged in relation to appropriate project milestones such as the Planning Agency issuing its opinion on the EIA.

International audiences engaged include a presentation by Carbfix on the project's EIA process at an international conference in Malaysia in May 2023 attended by international academia, NGO's and regulators.

Public acceptance

The main issues relevant to public acceptance are the project's environmental benefits and risks, well documented in the EIA report, stakeholder inputs to the report and the National Planning Agency's opinion on the report. Knowing and actively addressing stakeholder concerns in a transparent manner has been key to the success of the project and high public acceptance of Carbfix as a company. Quarterly national opinion polls reveal consistently high rates of positive public attitudes in Iceland towards Carbfix.