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DemoUpCARMA

WP3 – Demonstration of CO_2 transport and geological storage (abroad, CCTS)

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DEMO UP CARMA

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Zusammenfassung

Ziel dieses Arbeitspaketes ist es, die technische Machbarkeit der gesamten Supply-Chain mit (i) Verflüssigung des CO_2 bei einem Schweizer Industrieemittenten, (ii) grenzüberschreitendem CO_2-Transport und (iii) Speicherung des CO_2 in einem geologischen Reservoir im Ausland zu demonstrieren. Bei dem industriellen Emittenten handelt es sich um die Abwasserreinigungsanlage der Ara Region Bern, die hochreines biogenes CO_2 bereitstellt, das bei der Aufbereitung des im Prozess anfallenden Biogases entsteht. Neustark und Ara Region Bern betreiben eine beim Emittenten installierte Verflüssigungsanlage und stellen die Verladung des CO_2 in spezielle Iso-Container für den Transport sicher. Salzmann AG Transporte, SBB Cargo und ChemOil sind verantwortlich für den Transport der CO_2-Iso-Container vom Standort des Emittenten nach Rotterdam und zurück. Die Iso-Container werden per Lastwagen zum Bahnhof Weil-am-Rhein und von dort per Bahn zum Hafen Rotterdam transportiert. Der Transport vom Rotterdamer Hafen nach Reykjavik wird von einem Dienstleister (Samskip) durchgeführt und von Carbfix organisiert. Das transportierte CO_2 wird anschliessend in Wasser gelöst und zur permanenten Speicherung in eine basaltische Gesteinsformation injiziert. Carbfix ist verantwortlich für (i) die technische und geologische Charakterisierung des Standorts der Injektion (d. h. Feldcharakterisierung, Entwurf und Einrichtung des Injektionssystems, Probenahme und Charakterisierung der Lagerstättenflüssigkeit), (ii) den Bau des Injektionssystems und (iii) die Felddemonstration (d. h. CO_2-Injektion, chemische Überwachung, Überwachung des CO_2-Flusses).

Die Pilotinjektion wird die erste Injektion von in Meerwasser gelöstem CO_2 sein und an der neuen, von Carbfix gebauten und betriebenen Injektionsstelle durchgeführt werden. Nach der Durchführung wird die CO_2-Supply-Chain anhand festgelegter Leistungskennzahlen (Key Performance Indicators, KPIs) in Bezug auf technische, betriebliche, wirtschaftliche und ökologische Aspekte bewertet. Diese Arbeit wird (i) als Vorlage dienen für CO_2-Supply-Chains, die in Zukunft entwickelt werden, (ii) die Machbarkeit von CO_2-Supply-Chains beweisen und (iii) eine frühzeitige Identifizierung von technisch-ökonomischen, regulatorischen und ökologischen Herausforderungen ermöglichen, die vor dem Scale-up und der weiteren Entwicklung von CO_2-Supply-Chains adressiert werden sollten.

Résumé

L'objectif général de ce lot de travail est de démontrer la faisabilité technique de la chaîne logistique dans son intégralité avec (i) la liquéfaction du CO_2 sur le site d'un émetteur industriel suisse, (ii) le transport transnational du CO_2 et (iii) le stockage géologique du CO_2 à l'étranger. L'émetteur industriel en question est la station d'épuration des eaux usées Ara Region Bern, qui fournit du CO_2 biogénique de haute pureté résultant de la valorisation du biogaz produit à partir des eaux usées de la station. Neustark et Ara Region Bern gèrent et exploitent l'unité de liquéfaction installée sur le site de l'émetteur et s'occupent du chargement du CO_2 dans des conteneurs-citernes dédiés pour le transport. Salzmann AG Transporte, CFF Cargo et ChemOil assurent le transport des conteneurs-citernes de CO_2 du site de l'émetteur à Rotterdam et retour. Les conteneurs-citernes sont d'abord transportés par camion jusqu'à la gare de Weil-am-Rhein, puis par le rail jusqu'au port de Rotterdam. Le fret maritime des conteneurs-citernes du port de Rotterdam à Reykjavik est assuré par un prestataire de services (Samskip) et est géré par Carbfix. Le CO_2 transporté est ensuite dissous dans l'eau et injecté pour un stockage minéral permanent dans une formation rocheuse basaltique qui sert de réservoir de stockage permanent. Carbfix est chargé (i) de la caractérisation technique et géologique du site de démonstration (c'est-à-dire la caractérisation du terrain, la conception et la mise en place du système d'injection, et l'échantillonnage et la caractérisation des fluides du réservoir), (ii) de la construction du système d'injection, et (iii) de la démonstration sur le terrain (c'est-à-dire l'injection du CO_2, la surveillance chimique, et la surveillance du flux de CO_2).

Cette injection pilote sera la première dissolvant du CO_2 dans l'eau de mer et sera effectuée sur un nouveau site d'injection construit et exploité par Carbfix. Lors de sa mise en œuvre, la performance de la chaîne logistique de CO_2 sera évaluée sur la base d'indicateurs de performance clés (IPC) prédéfinis, relatifs aux aspects techniques, opérationnels, économiques et environnementaux. Ce travail (i) fournira un modèle de conception pour les chaînes logistiques de CO_2 qui seront développées à l'avenir, (ii) prouvera la faisabilité de telles chaînes, et (iii) permettra une identification précoce des lacunes techno-économiques, juridiques et environnementales qui devraient être comblées avant la mise à l'échelle et le développement ultérieur des chaînes logistiques de CO_2.

Summary

The overall purpose of this WP is to demonstrate the technical feasibility of the full supply chain with (i) CO_2 liquefaction at a Swiss industrial emitter, (ii) international cross-border CO_2 transport, and (iii) CO_2 geological storage abroad. The industrial emitter is the Ara Region Bern wastewater treatment plant, which provides a high purity biogenic CO_2 feedstock resulting from the upgrading of the biogas produced at their plant. Neustark and Ara Region Bern manage and operate the liquefaction unit installed at the emitter's facilities and take care of loading the CO_2 onto dedicated iso-containers for transport. Salzmann AG Transporte, SBB Cargo and ChemOil operate the transport of the CO_2 iso-containers from the emitter's site to Rotterdam and back. The iso-containers are transported by truck to the Weil-am-Rhein train station, and from there by rail to the port of Rotterdam. Sea freight from the port of Rotterdam to Reykjavik is operated by a service provider (Samskip) and is managed by Carbfix. The transported CO_2 is then dissolved in water and injected for permanent mineral storage in a basaltic rock formation, that serves as permanent storage reservoir. Carbfix is in charge (i) of the technical and geological characterization of the demonstration site (i.e., field characterization, injection system design and set-up, reservoir fluid sampling and characterization), (ii) of the construction of the injection system, and (iii) of the field demonstration (i.e., CO_2 injection, chemical monitoring, CO_2 flux monitoring).

This pilot injection will be the first injection of seawater-dissolved CO_2 and will be carried out at the new injection site built and operated by Carbfix. Upon its implementation, the performance of the CO_2 supply chain will be assessed based on defined key-performance indicators (KPIs) relative to technical, operational, economic, and environmental aspects. This work (i) will provide a blueprint design for CO_2 supply chains that will be developed in the future, (ii) will prove the feasibility of such chains, and (iii) will allow an early identification of techno-economic, regulatory, and environmental gaps that should be addressed prior to scale-up and further development of CO_2 value chains.

Contents

Abbreviations

BECCS	Bio-energy with CO_2 capture and storage
CCTS	Carbon dioxide capture, transport, and storage
DACCS	Direct Air Capture with CO_2 storage
GHG	Greenhouse gas
LCA	Life-cycle assessment
WP	Work Package

1 Introduction

1.1 Background information and current situation

Based on the pledges made in the frame of the Paris Agreement, Swiss emissions of greenhouse gases (GHG), particularly of carbon dioxide (CO_2), will have to be substantially curbed in the next three decades. Beside technology and infrastructural changes to eliminate distributed GHG emissions in sectors such as mobility and buildings, as of 2050 there will be the need to capture, transport and store millions of tons of CO_2 per year from large Swiss point sources (CO_2 capture, transport and storage, CCTS). These large emitters are waste-to-energy plants (currently 29 plants with total emissions of ca. 4.5 million tons CO_2/y; note that 50% of these consist of biogenic CO_2), cement manufacturing facilities (6 plants with current total emissions of ca. 2.5 million tons CO_2/y), chemical plants (with current total emissions of ca. 1 million tons CO_2/y). Moreover, negative CO_2 emissions, also in the order of millions of tons of CO_2 per year, will have to be generated to compensate for unavoidable residual emissions (e.g., from agriculture and aviation), through the deployment of e.g., Direct Air Capture with CCS (DACCS) and Bio-Energy with CCS (BECCS).

Avoiding or removing CO_2 emissions, by capturing fossil or biogenic CO_2, respectively, from point sources, and storing it permanently away from the atmosphere is one in a portfolio of solutions aimed at fulfilling Swiss climate goals, and it is the focus of this Work Package (WP).

CCTS and BECCS cannot rely on CO_2 underground storage sites in Switzerland today, and possibly not for the next 20+ years. In fact, the recently completed Elegancy project has reached such conclusion, while describing an updated roadmap to identify and make available for CO_2 storage suitable geological structures. Currently, CO_2 hubs are being developed mostly in North Sea (e.g., Northern Lights storage site or Carbfix Coda Terminal) and already now offer the possibility of storing CO_2 from European emitters.

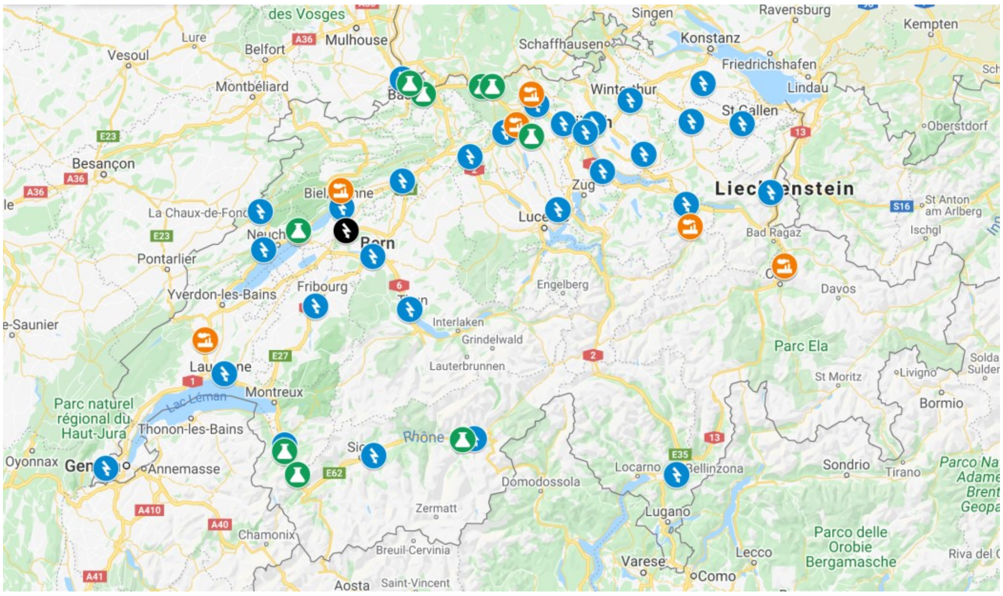

Figure 1. Geographical distribution of large-scale Swiss CO_2 emitters: Waste-to-Energy plants emitting ca. 4.5 $MtCO_2$/y (in blue), cement manufacturing plants emitting ca. 2.6 $MtCO_2$/y (in orange), and chemical plants emitting ca. 1.1 $MtCO_2$/y (in green). Note: Emissions data refer to year 2018.

The geographical distribution of the ca. 40 large scale Swiss CO_2 emitters (see Figure 1) and the need to collect the captured CO_2 and to convey it to locations where it is permanently stored make a CO_2 transport network necessary in Switzerland and in Europe. Such a network will most likely be based on pipelines and may require years or even decades to be built. Nevertheless, due to the urgency dictated by the global climate situation and the need of exploring the feasibility of such international CCTS solution, we aim to progress a first pathway connecting one CO_2 source in Switzerland to a CO_2 geological storage site abroad by deploying existing CO_2 transport solution.

1.2 Purpose of the WP/project

The overall purpose of this WP is to progress a CCTS pathway, whereby captured CO_2 is liquified, transported with different means of transportation, and stored permanently in the subsurface. More specifically, the WP aims at demonstrating the technical feasibility of the full supply chain with CO_2 liquefaction at a Swiss industrial emitter, international transport, and geological storage abroad. The industrial emitter is the Ara Region Bern (Bern) wastewater treatment plant, which provides a high purity biogenic CO_2 feedstock resulting from the upgrading of the biogas produced at the plant itself. Neustark and Ara Region Bern manage and operate the liquefaction unit installed at the emitter's facilities and take care of loading the CO_2 onto dedicated iso-containers for transport. Salzmann AG Transporte and SBB Cargo operate the transport of the CO_2 iso-containers from the emitter's site to Rotterdam and back. The iso-containers are transported by truck to the Weil-am-Rhein train station, and from there by rail to the port of Rotterdam. Sea freight from the port of Rotterdam to Reykjavik is managed by ETH and Carbfix. The transported CO_2 is then dissolved in water (i.e., in freshwater in the pre-tests, and in seawater for pilot tests) and injected for permanent mineral storage in a basalt rock formation, that serves as permanent storage reservoir. Carbfix is in charge (i) of the technical and geological characterisation of the demonstration site (i.e., field characterisation, injection system design and set-up, reservoir fluid sampling and characterisation), (ii) of the construction of the injection system, and (iii) of the field demonstration (i.e., CO_2 injection, chemical monitoring, CO_2 flux monitoring).

This work (i) will provide a blueprint design for CO_2 supply chains that will be developed in the future, (ii) will prove the feasibility of such chains, and (iii) will allow an early identification of techno-economic, regulatory, and environmental gaps that should be addressed prior to scale-up and further development of CO_2 value chains.

For this activity, the DemoUpCARMA project is closely linked to its "sister project" DemoUpStorage and to the Icelandic project CO_2SeaStone. While CO_2SeaStone covers the activities led by Carbfix regarding seawater CO_2 injection and geochemical monitoring, the companion project DemoUpStorage (with principal investigator ETH Prof. Stefan Wiemer), also partially funded and supported by the SFOE and by the FOEN in 2022, will use geophysical and geochemical monitoring techniques to track the propagation and mineralization of the CO_2 when injected into basalts.

1.3 Objectives

This WP has the following objectives:

- To demonstrate the feasibility of the full CCTS supply chain with CO_2 liquefaction at a Swiss industrial emitter, transport, and geological storage abroad.
- To demonstrate for the first time the injection and mineralization of CO_2 dissolved in seawater in subsurface basalt rock formation at the pilot scale.
- To assess the overall techno-economic and environmental (including life-cycle assessment) performance of the full CCTS supply chain and identify barriers and challenges to the implementation of future CO_2 value chains.

2 Description of facility

2.1 The CCTS supply chain

The CCTS supply chain consists of the following components:

- Liquefaction of CO_2 at Ara Region Bern and loading of the iso-containers. The industrial emitter is the Ara Region Bern (Bern) wastewater treatment plant, which provides a high purity biogenic CO_2 feedstock resulting from the upgrading of the biogas produced at the plant itself. The liquefaction unit, operated by Neustark, first dries, then compresses and finally cools the CO_2 so as it condenses yielding a liquid phase. The unit consumes electricity to power the compressor and the cooling system. After liquefaction, the CO_2 is loaded onto iso-containers for transport. For the pilot project, five iso-containers have been procured (from three different suppliers, i.e., Hoyer, meeberg and Karbonsan). The iso-containers are vacuum insulated and have a holding time of up to ca. 200 days (as indicated by the manufacturer). Each iso-container has a capacity of ca. 20 t liquid CO_2, which is loaded at a temperature of ca. -35°C and at a pressure of 15-18 bar. The pressure may increase during transport up to max. 22 bar; once this value is reached, a safety valve opens and releases the CO_2 until a pressure 10% lower than the max. value is attained.

Figure 2. Picture of iso-container.

- Transport of iso-containers from Ara Bern to the injection site in Iceland, split into:
  - Truck-based transport from Ara Bern to Weil-am-Rhein train station. The transportation of the iso-containers by truck in Switzerland is operated by Salzmann AG Transporte. The transport distance is of approximately 107 km and the truck transporting the iso-container uses biogas as fuel.
  - Train-based transport from Weil-am-Rhein to Rotterdam. On Saturdays, In Weil-am-Rhein the iso-containers are cleared through customs and are loaded onto rail (managed by ChemOil). The train travels through Switzerland, Germany, and the Netherlands (742 km).
  - Ship-based transport from Rotterdam to Reykjavik harbor. This transport is operated by the company Samskip, which is not a project partner but offers the transport as a service. The transport distance is of ca. 2200 km and the travel time is of ca. six days (subject to uncertainties related to weather conditions).
  - Truck-based transport from Reykjavik to the injection site (54 km, Helguvík and 29 km Hellisheiði). This transport is also operated by Samskip and managed by Carbfix.
- Injection of CO_2 in the underground for permanent storage. The injection is performed at two different sites:
  - At the existing Carbfix injection site at the Hellisheiði geothermal power plant. These pre-test injections are performed using fresh water as dissolving solution, as it is done routinely by Carbfix for ON Power, geothermal power plant, at the same site.
  - At the newly built injection site at Helguvík for pilot tests using seawater.
- Return of empty iso-containers to Switzerland for subsequent trips.

2.2 Planned schedule of the CCTS supply chain

The total round-trip time for the iso-containers transport is of 5 weeks, including one week layover in Iceland for offloading the CO_2 and one week layover at Ara Region Bern for uploading of the CO_2. According to the schedule, one full iso-container should depart every Friday from Ara Bern, while an empty one should arrive. Similarly, every Sunday one full iso-container should arrive at Reykjavik harbor and an empty one should depart from there every Wednesday. More specifically, the transport schedule is planned as follows:

- A full iso-container is delivered to the DUSS Terminal in Weil am Rhein before 7pm on Fridays (i.e., closing time).
- On Saturdays, the iso-container is loaded onto rail and transported to Rotterdam, where it arrives on Sundays.
- On Mondays, the iso-container is transferred from the Contargo Terminal to the Samskip Terminal. The cargo ship departs on Tuesdays from Rotterdam and arrives at Reykjavik harbor on Sundays.
- The iso-container is then transported to the injection site on Mondays or Tuesdays, and it is transported (empty) back to Reykjavik harbor on the following Mondays or Tuesdays (one week for offloading the CO_2).

2.3 CO_2 injection sites

In Iceland, Carbfix is responsible for injecting the CO_2 into the underground for permanent storage via mineralization. Carbfix has been pioneering this technology since the early 2010s, where CO_2 dissolved in water – a sparkling water of sorts – is injected into the subsurface where it reacts with favorable rock formations to form solid carbonate minerals via natural geochemical reactions that take about 2 years to complete.

Figure 3. Overview of the Helguvík injection site.

2.3.1 Helguvík injection site

For the first time, tests of CO_2 dissolved in seawater will be conducted at the pilot scale. The selected storage site for the CO_2 has been identified in Helguvík, see Figure 3. Prior to our projects (i.e., DemopUpCARMA, DemoUpStorage and CO_2SeaStone), there were no wells in this area that could be used for injecting CO_2. Therefore, new wells (for both injection and monitoring) have to be drilled.

At Helguvík, four new wells are being drilled: an injection well (1), a shallow monitoring well (2), a geophysical monitoring well (3) and a geochemical monitoring well (4). The technical details of the wells will be provided in the DemoUpStorage interim report.

A portable injection system will be installed at the site, in addition to a CO_2 vaporizer and a CO_2 temporary storage tank (supplied by Linde). Seawater will be supplied through an existing seawater well in the vicinity of the injection site.

2.3.2 Hellisheiði injection site

Pre-test injection of CO_2 using fresh water are conducted at the existing Carbfix well on the premises of its sister's company, ON Power Hellisheiði geothermal power plant. Further details on the motivation and background of these tests are provided in Section 4.

At Hellisheiði, liquid CO_2 from the iso-container is piped through a heat exchanger for vaporization. Gaseous CO_2 is then dissolved in freshwater and injected in the Carbfix injection well HN-14, see Figure 4.

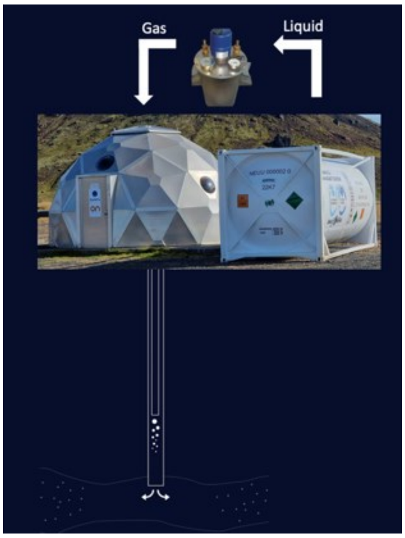

Figure 4. Schematic representation of the injection process at the Hellisheiði site.

3 Procedures and methodology

Upon implementation of the CCTS supply chain, data and measurements will be collected and evaluated to assess the techno-economic and environmental performance of the whole system. First, a set of key-performance indicators has been defined to evaluate the performance. Furthermore, a monitoring concept has been established to properly collect all relevant data and measurements. Finally, a rigorous life-cycle assessment will be carried out to determine the environmental impact following procedures defined in ISO 14040.

3.1 Key-performance indicators

The following KPIs have been identified:

- Primary energy consumption (possibly split in conditioning, transport, storage and in electricity vs. heat) (MJ/tCO_2);
- Total costs and costs per shipment split in: CO_2 supply (incl. liquefaction), CO_2 transport and CO_2 injection (EUR and EUR/shipment);
- Levelized costs of stored carbon (EUR/$tCO_{2,stored}$);

- Levelized costs of transported carbon (EUR/$tCO_{2,transported}$);
- Levelized costs of avoided carbon (EUR/$tCO_{2,avoided}$);
- Roundtrip duration (mean and variability, e.g., hours/trip);
- Transport emissions ($kgCO_2$-eq/$tCO_{2,transported}$);
- CO_2 avoidance efficiency (i.e. $tCO_{2\text{-eq,overall,chain}}/tCO_{2,stored}$);
- Carbon dioxide removal (i.e. $tCO_{2\text{-eq,overall,chain}}$ - $tbiogenicCO_{2,stored}$);
- CO_2 loading (mass of CO_2 per iso-container, tCO_2/shipment);
- LCA-related KPIs will follow the environmental footprint v3.0 standards, that include 15 life cycle impact categories as important and meaningful for the region of Europe and are thus applicable to this value chain (see Table 2 in subsection 3.3).

3.2 Monitoring concepts and measurements & data collection

Assessing the performance of the process requires the measurement of the key quantities needed to calculate KPIs defined in the previous section. Therefore, a monitoring concept has been established and is based on the following steps:

- Definition of the required data to be collected along the chain to ensure accurate evaluation of the system performance;
- Establishment of a procedure for continuous measurements and data collection;
- Collection of data used as inputs to the life-cycle assessment.

Continuous measurements and data collection enable to achieve the following objectives:

1. Accurately monitoring of the incurred costs;
2. Assessing the timing and logistics;
3. Determining how much CO_2 is captured, transported and permanently stored (i.e., eventually closing the CO_2 mass balance and estimating possible losses along the way);
4. Refining the LCA model with primary data.

The overview of measurements and data to be collected is provided in Figure 5 and details regarding the quantities measured, the points of measurements along the pilot supply chain and the relation to the objectives are provided in Table 1. Overall, the types of data that are collected can be broadly categorized in:

- Costs;
- Records of time and/or delays;
- Distances travelled;
- CO_2 mass flows and losses;
- Energy demands, i.e., electricity or fuel consumption;
- Infrastructure requirements (process equipment, iso-container etc.).

It should be noted that all data measured for each trip of the iso-containers is collected in a database to allow for comparative analysis of all the different trips.

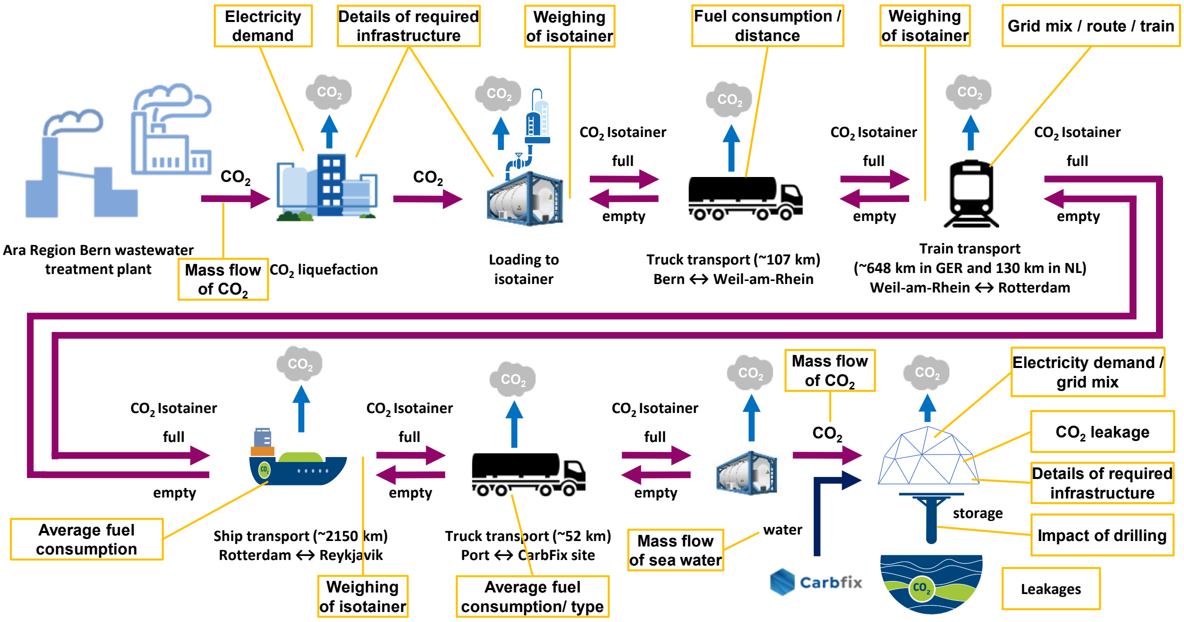

Figure 5. Overview of measurements and data collection upon the demonstration CCTS supply chain.

Table 1: Measurements and data collection in demonstration chain and relation to objectives.

Sensor / point of measurement or data collection	Measured quantity	unit	Required additional information	Measured in this part of the carbon capture, transport and storage chain						Objectives			
				Liquefaction	Truck transport in Switzerland	Rail transport	Ship transport	Truck transport in Iceland	Injection	Monitor costs	Assess timing / logistics	CO_2 mass balance	collect primary data to for LCA
Invoices from project partners	costs	CHF		X	X	X	X	X	X	X			
GPS sensor on iso-container	travel times	h	layover times	X	X	X	X	X	X		X		X
	length of distance travelled	km	route (train)		X	X	X	X					X
Sensor in liquefaction unit operated by Neustark	(average) mass flow of CO_2	kg/s	in-/outlet / purge	X								X	X
Truck / crane scale journey to Iceland	mass of iso-container (full)	kg	tara weight		X	X		X				X	X
Truck / crane scale journey to Switzerland	mass of iso-container (empty)	kg	tara weight		X	X		X				X	X
Detection of CO_2 leakage event through safety valve of iso-container	CO_2 pressure inside iso-container	bar	picture before and after un-/ loading		X			X				X	X
Estimation of CO_2 leakage during un-/loading of iso-container	volume of cryogenic transfer line	m³	gas exchange line used for un-/ loading?		X			X				X	X
Sensor above injection well head in Iceland	CO_2 concentration	ppm	only events > threshold						X			X	X
Sensor at injection site in Iceland operated by Carbfix	(average) mass flow of injected CO_2	kg/s	time integrated signal						X			X	X
Sensor at injection site in Iceland operated by Carbfix	(average) mass flow of injected sea water	kg/s	time integrated signal						X				X
Electricity consumption of machinery (pumps, liquefaction, monitoring, process control…)	electricity consumed	kWh	relevant local grid mix	X					X				X
(average) fuel consumption / emissions for transport	e.g., volume of fuel consumed	l	type of fuel/vehicle empty load factor		X	X	X	X					X
Country dependent electricity consumption for train transport	electricity consumed	kWh	relevant local grid mixes			X							X
Heat required for vaporisation of CO_2 in heat exchanger	amount of heat	kJ	heat source						X				X
Infrastructure requirements, e.g., steel / concrete / fluids / …	material mass	kg	process description; lifetime	X					X				X

Depending on the objective defined above, the source of the data to be collected and the measurements themselves may vary:

- Data relative to costs are retrieved from project partners or service providers, through e.g., invoices;
- Data relative to the schedule and timing of the various steps of the CCTS supply chain are requested from project partners; furthermore, an additional analysis of the data collected from a GPS data logger attached to the iso-containers is performed.
- For the calculation of the CO_2 mass balance, we rely on the measured mass flow of CO_2 during liquefaction (at Ara Bern) and injection (in Iceland), and on weight measurements of the iso-containers at key points along the CCTS supply chain for both inbound and outbound trips (i.e., upon departure/arrival by truck from/at Ara Bern, upon arrival/departure in Iceland, upon transfer of iso-containers from truck to train or from train to truck through a crane scale). In addition, a common weighing procedure has been defined to determine the tara weight as accurately as possible. Furthermore, we closely monitor process steps when CO_2 may leak, e.g., (i) during loading/offloading of CO_2 in/from iso-containers (e.g., verifying that a gas exchange line is used, calculating the volume of CO_2 vented from hoses), (ii) during possible opening of safety valve of iso-container due to overpressure during transport, and (iii) during CO_2 injection, through a CO_2 sensor placed above the injection well head.
- Primary data to refine the LCA are collected directly in the field during the implementation of the different steps of the CCTS supply chain (depending on availability):
  - CO_2 liquefaction:
    - Electricity consumption and grid mix for liquefaction and pumps at ARA Bern;
    - Vented CO_2 due to backflush in the drying process step;
    - Infrastructure requirements (pumps, piping, process control);
  - CO_2 transport:
    - Type of fuel, consumption, distance travelled and empty load factor of truck in Switzerland;
    - Route, distance travelled and grid mix for train transport;
    - Type of fuel and ship, average consumption and distance for ship transport;
    - Type of fuel and truck, average consumption and distance travelled for truck transport in Iceland;
  - CO_2 injection:
    - Volume flow of seawater used for injection;
    - Electricity consumption and grid mix for seawater pump, CO_2 pump, process control;
    - Amount of heat and its source for CO_2 vaporizer;
    - Infrastructure requirements (pumps, piping, process control).

3.3 Life-cycle assessment

A life-cycle assessment is performed to evaluate the environmental performance of the CCTS supply chain for its fully life cycle based on well-established key performance indicators and on a cradle-to-grave approach (see Figure 6 left). Furthermore, assessing multiple impact categories (e.g., climate change, fossil resource depletion and toxicity) over the full life cycle allows to detect burden shifting (see Figure 6 left).

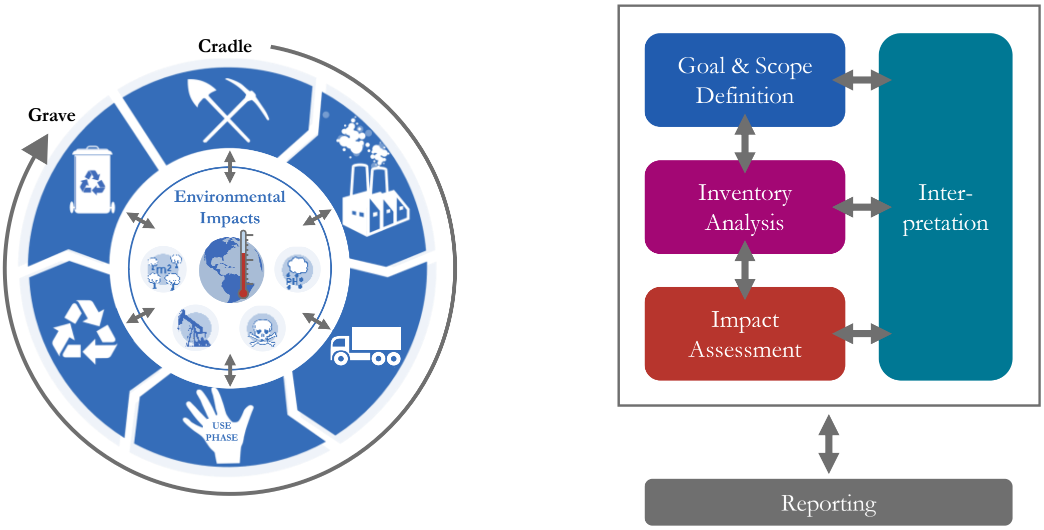

Figure 6: Life Cycle Assessment (LCA): Evaluation of environmental impacts of the entire life cycle from cradle to grave (left). The relation of the four steps in LCA according to ISO 14040 (right).

All methodological choices (assumptions, models, etc.) within the LCA are aligned with the LCA performed by PSI for the other demonstration chain in the project (WP2). The assessment of the overlapping part of the chain, i.e., the liquefaction at ARA Bern is foreseen to be identical in both LCAs to ensure consistency.

The LCA follows the standardization in ISO 14040 including the iteratively performed steps shown in Figure 6, right.

3.3.1 Goal & Scope Definition

The LCA to be performed on the CCTS supply chain implemented in WP3 aims at assessing the potential environmental impacts of the overall supply chain over its entire life cycle. The key output of the analysis is the evaluation of the net negative emissions the overall chain generates, i.e., the net amount of CO_2 taken from the atmosphere and permanently stored, when considering all greenhouse gas emissions caused by the entire life cycle of the overall supply chain. In addition, the LCA aims at assessing a wide range of environmental impact categories to identify possible burden shifting from the global warming impact towards other impact categories.

Next, the scope of the study is established in line with the stated goal. The scope includes the definition of the functional unit, the information on the model underlying data and its quality, the approach to multifunctionality and cut-off, and the impact assessment method. The system boundary is shown in Figure 7 and is discussed in the inventory analysis step below.

The intended target audience for the LCA consists in the members of the DemoUpCARMA project consortium, the funding agencies (i.e., BFE and BAFU), the CCTS community and the general interested public. As the goal of WP3 is to demonstrate the permanent storage of Swiss biogenic CO_2, this work focuses on **“the storage of 1 kg of CO_2” as the functional unit**. The background processes are modeled using aggregated datasets from the **ecoinvent 3.8 database with the allocation, cut-off method**. The database version 3.8 was the most up-to-date version of ecoinvent available in the LCA framework Brightway2 when the project started. Due to the wide acceptance of the ecoinvent database in industry and its continuous updating, data quality is regarded as sufficient for this study. In general, data is most preferred when reflecting country-specific production, followed by European production. If neither is available, other production regions are selected as substitutes. The assessed demonstration chain **does not include multifunctional processes in the foreground system and no cut-off is applied** to capture the full environmental impact of the chains. However, this does not mean that all possible inputs and outputs are captured; it rather means that none of the currently known inputs and outputs are neglected. The LCA follows the recommendation of the European Commission using the **Product Environmental Footprint version 3 (EF 3.0) environmental impact assessment methods** as implemented in the ecoinvent 3.8 database. Carbon capture, transport and storage (CCTS) chains can have various effects on the environment. While they are applied to reduce the climate impacts, CCTS chains often shift the environmental burden to other impact categories. Thus, we analyse all environmental impact categories included in the EF 3.0. An overview of the impact categories considered can be found in Table 2.

Table 2: Impact categories assessed in the LCA based on ILCD recommendations. Recommendation level I: recommended and satisfactory. Recommendation level II: recommended but in need of some improvement. Recommendation level III: recommended but to be applied with caution.

Impact category	Unit	Recommendation level
Climate Change	kg CO_2 eq.	I
Ozone depletion	kg CFC-11 eq.	I
Ionizing radiation	kBq U235 eq.	II
Photochemical ozone formation	kg NMVOC eq.	II
Acidification terrestrial and freshwater	mol of H+ eq.	II
Eutrophication freshwater	kg P eq.	II
Eutrophication marine	kg N eq.	II
Eutrophication terrestrial	mol of N eq.	II
Respiratory inorganics	Disease incidences	II
Resource use, energy carriers	MJ	II
Resource use, mineral and metals	kg Sb eq.	II
Human toxicity, cancer	CTUh	III
Human toxicity, none-cancer	CTUh	III
Ecotoxicity	CTUe	III
Resource depletion, water	m^3 world equiv.	III

In accordance with the ILCD guideline and the PEF3.0, **biogenic carbon streams are assumed to have zero impacts**. The combustion of fuels to meet the heat demand results in carbon emissions for fossil fuels (e.g., natural gas), but not for bio-based fuels like biogas. However, it should be noted that the combustion of biogenic fuels still results in a climate impact, for example, from the preparation and transport of the biogenic fuels and the formation of other components in the combustion gases. The LCA for DemoUpCARMA is conducted with **Brightway2**, an open-source framework for life cycle assessment written primarily in Python, and the **activity browser**, an open-source software that builds on top of the Brightway2 framework. All processes are modeled with the Brightway2 framework and the activity browser software. The ecoinvent cut-off database 3.8 is imported for usage in Brightway2. The Life Cycle Impact Assessment is conducted with the product environmental footprint 3.0 (PEF3) method as imported from ecoinvent to the Brightway2 framework. Further **aggregation and visualization of the results are conducted in Excel**.

3.3.2 Inventory Analysis: System boundary and life cycle inventory

The LCA includes all processes and their energy and mass flows to and from the environment shown within the red-dotted system boundary in Figure 7. The data collection follows a 2-layers approach:

1. Preliminary LCA model (data from databases, literature & prior work);
2. Refined LCA model (data from project partners, modeling and monitoring).

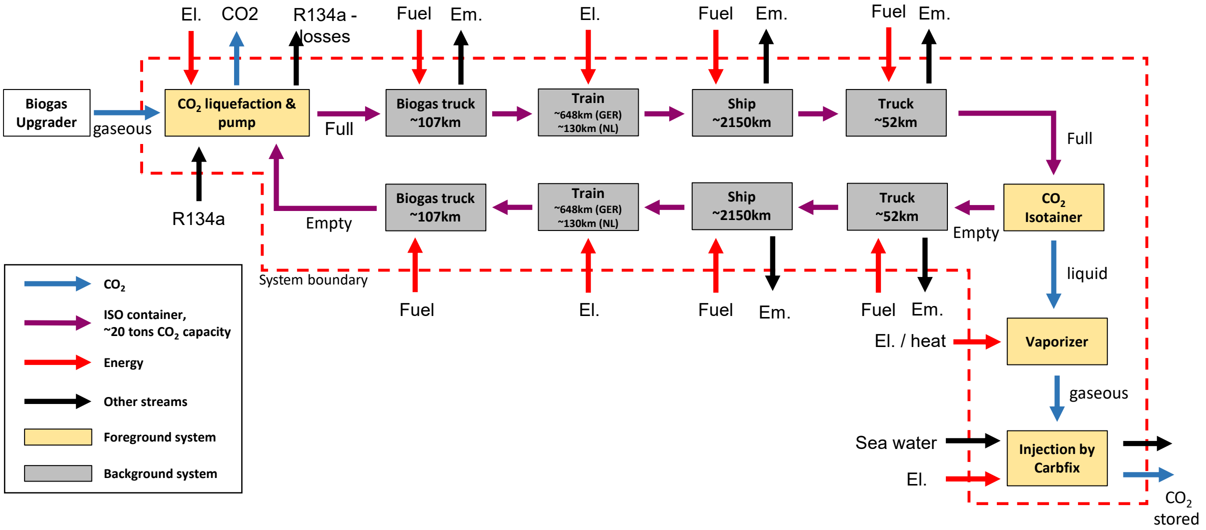

Figure 7: System boundary and streams for LCA of demonstration chain including processes modelled in the foreground system and processes of the background system.

4 Activities and results

4.1 Status of the Helguvík injection site

In Spring 2022, it was decided to move the CO_2 injection site to Helguvík for (i) accommodating larger CO_2 quantities in view of a scale-up project, and (ii) enabling a more effective and accurate monitoring system of the CO_2 injection. Nevertheless, unexpected challenges in harmonizing the design for the injection and monitoring wells emerged. This has led to a new wells' arrangement and to time delays. Furthermore, additional funding for drilling and installation of the relevant instrumentation (beyond what had already been planned and budgeted) had to be raised. This amounts to ca. 5% of the overall budget (for the three projects combined, i.e., DemoUpCARMA, DemoUpStorage and CO_2SeaStone). The extra budget will be supplied by ETH (through support from ETH Foundation) and Carbfix (in approximately equal parts).

The preparation of the injection site in Helguvík, see Figure 8, has started on August 29th, 2022. Several challenges were encountered upon drilling of the wells, e.g., faulty casing, clogging of the hammer, etc. Currently, both the geochemical monitoring well and the shallow well have been drilled. The injection well is currently being drilled. The site is expected to be ready before Christmas 2022. Once the site is ready, baseline measurements for geophysical monitoring will have to be collected prior to injection. At this point in time, the injection of CO_2 with seawater is expected to start in February/March 2023.

Due to these delays at the Helguvík injection site, it was decided to move forward with the cross-border shipments of CO_2 and with its injection in Iceland using one of the existing Carbfix wells at the Hellisheiði geothermal power plant. These injection pre-tests to be done with fresh water would allow to de-risk the seawater injection at Helguvík and the transport itself, by identifying early on obstacles and challenges and proposing solutions as needed.

Figure 8. Picture of the Helguvik injection site in preparation, Summer 2022.

4.2 Status of CO_2 cross-border shipments

Because of time delays with the Helguvík injection site and the implementation of the temporary injection solution at Hellisheiði, it was decided in Summer 2022 to start with the shipments of one iso-container every two weeks.

The first iso-container was shipped on July 29th, 2022 and it arrived at Reykjavik harbor on August 7th, 2022. A schematic representation of the first CCTS supply chain implemented as well as pictures thereof is shown in Figure 9. A second container was shipped on August 12th, 2022, and it arrived at Reykjavik harbor on August 22nd, 2022.

Although no issues were encountered upon export of the CO_2 from Switzerland, a first regulatory challenge had to be faced upon import of the first iso-container in Iceland. The Icelandic Environmental Protection Agency had initially raised concerns about classification of CO_2 (chemical product vs. waste). A proof of origin for the CO_2 was provided to the Agency upon its request. Iceland has implemented the EU CCS Directive into the hygiene and pollution prevention law nr. 7/1998. However, the project does not fall under this Directive because it is a R&D project, and the amount of CO_2 to be stored is less than 100’000 tons (above which the Directive would apply). Therefore, the Icelandic Environmental Protection Agency could not process the custom documents in accordance with the EU Directive. For this reason, it was initially unclear under which law this import of CO_2 would fall, e.g., under waste law. Finally, on August 25th, 2022, the Agency decided to “release” from customs the two containers already arrived in Reykjavík. The Agency agreed to exempt the CO_2 from Icelandic waste regulations as it “belongs” to a research project. Ultimately, the first two containers were delivered to Hellisheiði on September 7. The third and fourth iso-containers were shipped on August 26th, 2022 and September 9th, 2022, and then also delivered to Hellisheiði.

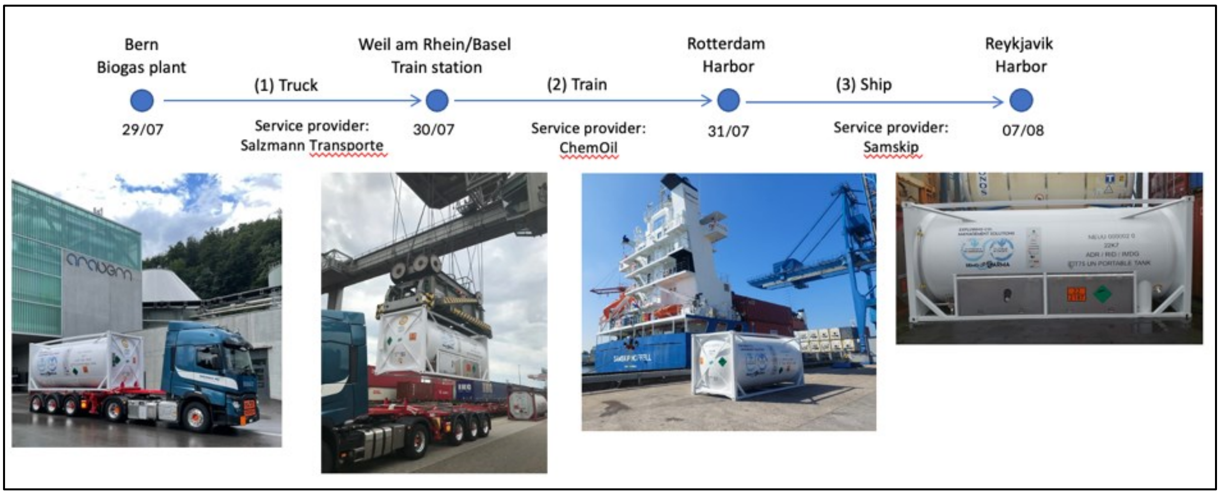

Figure 9. Scheme and pictures of the first CCTS supply chain implemented.

After the first shipment, bilateral discussions between the Agency and the Industrial Waste Section at the Swiss Federal Office for the Environment (FOEN) took place. The latter has informed Neustark (as the CO_2 supplier) on September 15th that:

- In Switzerland, according to Art. 7 (6) of the Environmental Protection Act (USG), waste is movable property which the holder discards or whose disposal is required in the public interest;
- Shipment of CO_2 to Iceland for final underground storage implies the willingness to dispose of the waste and also an act of disposal. In this case, CO_2 is destined for disposal (e.g. underground storage/deposition) and is therefore considered waste under Swiss law;
- Transboundary movement of waste requires a permit under waste law from the FOEN in accordance with the Basel Convention;
- For the FOEN to issue an export permit under waste law for the export of CO_2 for storage in the Icelandic subsurface, the Swiss exporter must submit an application;
- After consultation with the competent Icelandic authority, it has been established that these shipments do not fall under transboundary waste legislation according to the Icelandic legislation, therefore a *Unilateral export permit* will be issued by the FOEN (which does not need the involvement nor the approval of the Icelandic authority).

As of November 2022, the WP3 project partners (i.e., Neustark, Carbfix, ETH) are preparing the documentation needed to apply for this export permit and are verifying that there are no concerns from the authorities of the transiting countries (i.e., Germany and the Netherlands). In the meantime, the CO_2 shipments to Iceland have been idled until these regulatory requirements have been met.

4.3 Status of CO_2 injection at Hellisheiði

For the pre-tests of CO_2 injection at Hellisheiði, additional equipment was required, namely a CO_2 evaporator and relevant fittings. Carbfix had purchased an evaporator from Pangas but the purchase has a long lead time due to the global supply chains situation and has not yet been delivered to Iceland (November 2022). As an alternative solution, a small CO_2 evaporator was rented by Carbagas (Trafar) and shipped from Switzerland. The evaporator was delivered to Hellisheiði on September 8th. Nevertheless, additional adaptions to the injection system had to be made (e.g., procuring additional flanges and process equipment). The full set-up was completed at the beginning of November and CO_2 injection has started on November 4th, 2022. The four iso-containers delivered to Iceland in August and early September 2022 will be offloaded in the upcoming weeks. It should be noted that currently the injection rate is limited by the small capacity of the rented evaporator (ca. 100 kgCO_2/h). Once the four containers are “emptied”, they will be returned to Switzerland for further shipments.

5 Evaluation of results to date

A few outcomes and learnings obtained so far from the activities in WP3 are summarized in the following:

- The CO_2 transport solution is feasible from a technical point of view, although unforeseen regulatory requirements are causing an additional administrative burden (i.e., application for unilateral waste handling permit). Furthermore, this indicates that there is the need to harmonise European and Swiss waste legislations in view of both project continuation and scale-up initiatives from both Swiss and Icelandic sides (e.g., Coda Terminal).
- Net negative emissions can be generated through this CCTS supply chain under the assumption that a high biogenic content of the CO_2 streams is guaranteed (the CO_2 captured from the biogas upgrader of the wastewater treatment plant ARA Bern is certified to be 100% of biogenic origin); not-yet decarbonized international CO_2 transport is responsible for the largest contribution to the environmental impact of such solution. Please note that these preliminary estimates may change, especially after further alignment with the LCA carried out in WP2.
- Solving the issues related to waste regulations require coordination at international level to be solved and should be addressed early on, as they could have an impact on other implementation aspects, including public acceptance.
- The global economic and geopolitical situation has made material procurement challenging during the first year of the DemoUpCARMA project.

6 Next steps

For the upcoming months, the following activities are planned:

- Completion of injection of CO_2 from the four iso-containers currently in Iceland into the Carbfix well at Hellisheiði;
- Application for unilateral waste handling permit and resumption of CO_2 shipments to Iceland under new regulatory requirements;
- Completion of Helguvík injection site and start of injection with seawater;
- Collection of pilot-tests data concerning costs and environmental impact of the CCTS chain and final assessment.

It is worth noting that as soon as the preparation for injection in Helguvík is completed and the export from Switzerland to Iceland of the CO_2 iso-containers is permitted by FOEN, it will be possible to make a new schedule of CO_2 transport and injection. Accordingly, the schedule of the activities around WP3 will be revised and discussed with the funding agencies and project partners.

7 National and international cooperation

The project and this work package in particular rely on the international cooperation between Switzerland and Iceland. This cooperation has been further strengthened through the interim WP3 review held in Iceland on September 12-13, 2022, during which the project partners involved in this WP gathered in Iceland, together with members of BFE and BAFU, to discuss about the WP progress and to visit the injection sites at Helguvík and Hellisheiði.

8 Communication

Not applicable since the project communication is being dealt with in Work Package 1.

9 Publications

Not applicable.

10 References

Not applicable.

11 Appendix

Not applicable.