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DemoUpCARMA

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

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Zusammenfassung

In diesem Arbeitspaket haben wir erstmals die technische Machbarkeit der gesamten Lieferkette demonstriert: (i) die CO_2-Verflüssigung bei einem Schweizer Industrieemittenten, (ii) den internationalen grenzüberschreitenden CO_2-Transport und (iii) die CO_2-Injektion im Ausland in einem Onshore-Reservoir umfasst. Der industrielle Emittent ist die ara region bern ag, welche hochreines biogenes CO_2 aus der Aufbereitung des vor Ort erzeugten Biogases liefert. Neustark und die ara region bern ag sind für das Management und den Betrieb der Verflüssigungsanlage sowie für die Verladung des CO_2 in spezielle Iso-Container für den Transport verantwortlich. Salzmann AG Transporte, SBB Cargo und ChemOil übernehmen den Transport der CO_2-Iso-Container vom Standort des Emittenten nach Rotterdam und zurück. Die Container werden per Lastwagen zum Bahnhof Weil-am-Rhein und anschliessend per Bahn zum Hafen Rotterdam transportiert. Die Seefracht vom Hafen Rotterdam nach Reykjavik wird vom Dienstleister Samskip abgewickelt und von ChemOil und Carbfix überwacht. In Island löst der Carbfix-Prozess CO_2 in Wasser und injiziert es dann in basaltisches Grundgestein. Carbfix hat in früheren Projekten bereits gezeigt, dass CO_2 in Süsswasser gelöst und in den Untergrund injiziert werden kann, wo es anschliessend mineralisiert. Die Projekte DemoUpCARMA und DemoUpStorage haben demgegenüber erstmals die Injektion von CO_2 demonstriert, das vor Ort in Meerwasser gelöst wurde.

Die erste Injektionskampagne fand zwischen Herbst 2022 und Frühjahr 2023 statt und umfasste die Injektion von rund 50 Tonnen CO_2 am Standort Hellisheiði mit Süsswasser. Eine zweite Kampagne zwischen Herbst 2023 und Herbst 2024 injizierte etwa 140 Tonnen CO_2, gelöst in Meerwasser, am Standort Helguvík, der im Rahmen der Projekte DemoUpCARMA, DemoUpStorage und CO_2SeaStone durchgeführt wurde. Die Überwachung der Injektion wurde im Rahmen des Projekts DemoUpStorage durchgeführt. Die Ergebnisse und die Leistungsfähigkeit der Injektion von in Meerwasser gelöstem CO_2, insbesondere in Bezug auf die Mineralisierung, sind im DemoUpStorage-Projektbericht dokumentiert.

Während der Betriebsphase traten mehrere Herausforderungen auf, darunter die Komplexität regulatorischer Anforderungen, Wissenslücken beim Personal aufgrund der Neuartigkeit der Technologie, die Entwicklung eines wirksamen Protokolls zur CO_2-Verfolgung und -Überwachung auf Systemebene, unerwartete Probleme in der Lieferkette und beim Anlagenbau sowie logistische Herausforderungen, etwa Gleisbauarbeiten in Deutschland im Sommer 2024, die zu Verzögerungen beim Containertransport führten. Trotz dieser Hürden demonstrierte das Projekt erfolgreich das Potenzial des grenzüberschreitenden CO_2-Transports und der unterirdischen Mineralisierung als wirksame Instrumente zur Emissionsreduktion und Carbon Dioxide Removal. Diese Pionierarbeit zeigt die realen Herausforderungen bei der Umsetzung innovativer Konzepte und betont die Bedeutung, regulatorische, fachliche und logistische Hindernisse direkt im Feld, beispielsweise durch Pilotprojekte, anzugehen.

Für die demonstrierte CO_2-Lieferkette betragen die Kosten für die Beschaffung und den Transport von verflüssigtem CO_2 von der Ara Bern Biogasaufbereitungsanlage in der Schweiz nach Island etwa 1'600 CHF pro Tonne. Kostensenkungen werden erwartet, wenn künftig von Containertransport (wie in diesem Projekt) auf Pipeline-Transport umgestellt wird, wie in WP4 adressiert. Die Lebenszyklusanalyse zeigt eine Effizienz von über 70 %, wobei das gesamte erfasste CO_2 als biogen zertifiziert ist und somit Netto-Negativemissionen ermöglicht. Über 75 % der Umweltwirkungen stammen aus dem heute noch fossil geprägten internationalen Transport, was die Bedeutung des Aufbaus einer CO_2-Transportinfrastruktur mit niedrigen Emissionen parallel zur Dekarbonisierung von Energie und Schifffahrt unterstreicht.

Résumé

Dans ce projet, nous avons démontré pour la première fois la faisabilité technique de l'ensemble de la chaîne d’approvisionnement comprenant (i) la liquéfaction du CO_2 chez un émetteur industriel suisse, (ii) le transport international transfrontalier du CO_2, et (iii) l’injection de CO_2 dans un réservoir de stockage géologique onshore situé à l’étranger. L’émetteur industriel est la station d’épuration d’ara region bern ag, qui fournit du CO_2 biogène de haute pureté issu de la valorisation du biogaz produit sur site. Neustark et ara region bern ag sont responsables de la gestion et de l’exploitation de l’unité de liquéfaction installée sur le site de l’émetteur, ainsi que du chargement du CO_2 liquide dans des conteneurs iso dédiés au transport. Salzmann AG Transporte, CFF Cargo et ChemOil assurent le transport des conteneurs iso du site de l’émetteur vers Rotterdam et retour. Les conteneurs sont transportés par camion jusqu’à la gare de Weil-am-Rhein, puis par rail jusqu’au port de Rotterdam. Le transport maritime du port de Rotterdam à Reykjavik est assuré par le prestataire Samskip et supervisé par ChemOil et Carbfix. Carbfix a déjà démontré, dans des projets antérieurs, que le CO_2 peut être dissous dans de l’eau douce et injecté dans le sous-sol, où il se minéralise ensuite. Les projets DemoUpCARMA et DemoUpStorage ont en revanche démontré pour la première fois l’injection de CO_2 dissous sur site dans de l’eau de mer.

La première campagne d’injection, menée entre l’automne 2022 et le printemps 2023, a permis d’injecter environ 50 tonnes de CO_2 au site d’Hellisheiði en utilisant de l’eau douce. Une deuxième campagne, menée entre l’automne 2023 et l’automne 2024, a injecté environ 140 tonnes de CO_2 dissous dans de l’eau de mer au site d’Helguvík, construit dans le cadre des projets DemoUpCARMA, DemoUpStorage et CO_2SeaStone. La surveillance de l’injection a été réalisée dans le cadre du projet DemoUpStorage. Les résultats et les performances de l’injection de CO_2 dissous dans l’eau de mer, notamment en ce qui concerne la minéralisation, sont documentés dans le rapport du projet DemoUpStorage.

La phase opérationnelle du projet a révélé plusieurs défis: complexité de la conformité réglementaire, manque de connaissances du personnel en raison de la nouveauté de la technologie, développement d’un protocole efficace de suivi et de traçabilité du CO_2 à l’échelle du système, problèmes imprévus dans la chaîne d’approvisionnement et lors de la construction du site, ainsi que des défis logistiques tels que des travaux ferroviaires en Allemagne durant l’été 2024 ayant provoqué des retards d’expédition. Malgré ces difficultés, le projet a démontré avec succès le potentiel du transport transfrontalier du CO_2 et de la minéralisation souterraine comme outils efficaces pour réduire les émissions et retirer du CO_2 de l’atmosphère. Cet effort pionnier met en lumière les complexités réelles liées à la mise en œuvre de concepts innovants et souligne l’importance de relever les défis réglementaires, techniques et logistiques directement sur le terrain, notamment au moyen de projets pilotes.

Pour la chaîne d’approvisionnement démontrée, l’approvisionnement et le transport du CO_2 liquéfié depuis l’unité d’épuration de biogaz d’Ara Bern jusqu’à l’Islande coûtent environ 1'600 CHF par tonne, reflétant une opération de première mise en œuvre. Des réductions de coûts sont attendues avec le passage du transport par conteneurs (comme démontré dans ce projet) au transport par pipeline, comme étudié dans le WP4. L’analyse du cycle de vie montre une efficacité supérieure à 70 %, tout le CO_2 capté étant certifié biogène, permettant ainsi d’atteindre des émissions nettes négatives. Plus de 75 % des impacts environnementaux proviennent du transport international encore largement fondé sur les combustibles fossiles, ce qui souligne la nécessité de développer une infrastructure de transport du CO_2 à faibles émissions parallèlement à la décarbonisation en cours du secteur énergétique et du transport maritime.

Summary

In this WP, we have demonstrated, for the first time, the technical feasibility of the entire supply chain involving (i) CO_2 liquefaction at a Swiss industrial emitter, (ii) international cross-border CO_2 transport, and (iii) CO_2 injection in the subsurface in an onshore reservoir located abroad. The industrial emitter is the Ara Bern wastewater treatment plant, which supplies high-purity biogenic CO_2 resulting from upgrading the biogas produced on-site. Neustark and ara region bern ag are responsible for managing and operating the liquefaction unit installed at the emitter's facilities and for handling the loading of CO_2 into dedicated iso-containers for transport. Salzmann AG Transporte, SBB Cargo, and ChemOil are the operators responsible for transporting the CO_2 iso-containers from the emitter's location to Rotterdam and back. The iso-containers are transported by truck to the Weil-am-Rhein train station and then by rail to the port of Rotterdam. The sea freight from the port of Rotterdam to Reykjavik is managed by the service provider Samskip and is overseen by ChemOil and Carbfix. In Iceland, the Carbfix process dissolves CO_2 in water and then injects it into basaltic bedrock. In previous projects, Carbfix has already demonstrated that CO_2 can be dissolved in freshwater and injected into the subsurface, where it subsequently mineralizes. In contrast, the DemoUpCARMA and DemoUpStorage projects have, for the first time, demonstrated the injection of CO_2 dissolved in seawater.

The initial injection campaign, conducted between Autumn 2022 and Spring 2023, involved injecting approximately 50 tons of CO_2 into the Hellisheiði site using freshwater. A second campaign, held between Autumn 2023 and Autumn 2024, injected about 140 tons of CO_2 mixed with seawater at the Helguvík site, constructed under the frameworks of the DemoUpCARMA, DemoUpStorage and CO2SeaStone projects. The monitoring of the injection was carried out within the framework of the DemoUpStorage project. The results and performance of the injection of CO_2 dissolved in seawater, particularly with regard to mineralization, are documented in the DemoUpStorage project report.

The operational phase of the project revealed several challenges, including the complexity of regulatory compliance, knowledge gaps among personnel due to the novelty of the technology, the development of an effective CO_2 tracking and monitoring protocol at the system level, unexpected issues in the supply chain and site construction, and logistical challenges such as railway maintanance and construction in Germany during summer 2024 that caused delays in container shipments. Despite these operational hurdles, the project successfully demonstrated the potential of cross-border CO_2 transport and of subsurface mineralization as effective tools for emissions reduction and for CO_2 removal. This pioneering effort highlights the real-world complexities of transitioning innovative concepts into practice and emphasizes the importance of addressing regulatory, knowledge, and logistical challenges directly in the field through for instance pilot projects.

For the demonstrated CO_2 supply chain, sourcing and transporting liquefied CO_2 from the Ara Bern biogas upgrading plant in Switzerland to Iceland costs around 1,600 CHF per ton, reflecting a first-of-a-kind operation. Reductions in CO_2 transport costs are expected when shifting from container-based transport (as what demonstrated in this project) to pipeline-based transport, as addressed in WP4. Life-cycle analysis shows an efficiency above 70%, with all captured CO_2 certified as biogenic, enabling net-negative emissions. Over 75% of environmental impacts stem from fossil-based international transport, underscoring the importance of developing low-carbon, large-scale CO_2 transport infrastructure alongside ongoing decarbonization of energy and shipping.

Main findings

- The established CO_2 supply chain is technically feasible, demonstrating that the transportation of CO_2 across borders for permanent storage is achievable using existing logistic solutions. CO_2 originating from a land-locked country like Switzerland can be transported and injected in an underground geological formation abroad, offering a method to reduce or remove emissions using available technologies. The use of freshwater for injection has been successful, while injection with seawater has been tested at the pilot scale in Helguvík with promising mineralization results.
- From an operational standpoint, several challenges have arisen due to the innovative nature of this pilot project carried out in a new site and with new technology. These challenges can be classified into several categories: (1) Regulations related to the classification of CO_2 (chemical product vs. Waste stream) have increased administrative burdens associated with operations compared to what was initially expected under the assumption of exporting CO_2 simply as dangerous chemical product. (2) Limited knowledge and experience among personnel (inside and outside the project) regarding CO_2 logistics and the novelty of the topic have resulted in slow initial progress. (3) The establishment of a well-defined CO_2 monitoring procedure at the system level has proven challenging, affecting accurate tracking of CO_2. (4) Unexpected issues related to the pilot implementation and to its operations, such as unexpected water content in the iso-containers, have arisen. (5) Issues stemming from the construction and operation of the injection site, particularly during a challenging period marked by the COVID-19 pandemic and the Ukraine conflict, as well as in less-than-optimal weather conditions in Iceland, have affected the project progress. (6) Being a first-of-a-kind initiative, the project has faced typical start-up challenges such as operational uncertainties and difficulties related to the construction of the wells.
- From an economic standpoint, the current technology is expected to cost several hundred Swiss francs per ton of CO_2 stored in the short to medium term. In this project, sourcing and transporting liquefied CO_2 from a biogas upgrading plant in Switzerland to Iceland has led to costs of around 1,600 CHF per ton of CO_2 transported. This figure, however, reflects a first-of-a-kind operation and is therefore higher – possibly much higher - than what would be expected for an Nth-of-a-kind deployment. As outlined in WP4, costs are anticipated to decrease in the future.
- From a life-cycle environmental perspective, the demonstrated CCTS chain is expected to reduce GHG emission. The life-cycle CCTS efficiency exceeds 70 %, meaning that GHG emissions resulting from the life-cycle analysis of conditioning, transport, and geological storage are far lower than the amount of GHG emissions reduced. Furthermore, the CCTS supply chain can contribute to net-negative greenhouse gas emissions if the share of CO_2 captured of biogenic origin is sufficiently high. For the wastewater treatment plant Ara Bern, all of the CO_2 captured from the biogas upgrader is certified to be of biogenic origin. An overwhelming share of over 75 % of the environmental impacts of the demonstrated CCTS chain is due to fossil-based international transport. Hence, planning international CO_2 transport infrastructure requires particular attention. We expect that through the introduction of large-scale transport infrastructure the environmental impact of future CCTS chains will decrease, and that this will be accelerated by a continuing defossilization of the European electricity grid and by stricter environmental regulations for shipping and freight transport.

Contents

Abbreviations

BECCS	Bio-energy with CO_2 capture and storage
CCTS	Carbon dioxide capture, transport, and storage
CCUS	Carbon dioxide capture, use and storage
CO_2	Carbon dioxide
DAC	Direct air capture
DACCS	Direct air capture with CO_2 storage
FOEN	Federal Office for the Environment
GHG	Greenhouse gas
KPI	Key performance indicator
LCA	Life-cycle assessment
RCA	Recycled concrete aggregates
SFOE	Swiss Federal Office of Energy
VAT	Value added tax
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 carbon dioxide (CO_2), have to be curbed substantially in the next three decades. Besides 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 CO_2 on a megaton-scale annually from large Swiss point sources (CO_2 capture, transport, and storage, CCTS). These large point-source 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, megaton-scale negative CO_2 emissions have to be generated annually to compensate for unavoidable residual emissions, e.g., from agriculture and aviation, through the deployment of carbon dioxide removal technologies such as direct air capture with CO_2 storage (DACCS) and bio-energy with CCS (BECCS) [1].

Reducing or removing CO_2 emissions by capturing fossil or biogenic CO_2, respectively, from point sources and permanently storing CO_2 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. The recently completed Elegancy project[2] has concluded that while Switzerland's geology may hold potential for CO_2 storage, significant work is required to identify and develop suitable geological structures. Currently, there is no operational experience with CO_2 storage in the country, and the extent of its underground storage capacity remains unclear. The CITru pilot project (CO_2-Pilotinjektion in Trüllikon)[3] marks a crucial step toward understanding the feasibility of CO_2 storage in the country. Initial studies suggest that Switzerland's geology, particularly at depths of over 1,000 meters, may be suitable for long-term CO_2 storage. The project is currently in the exploratory phase, involving seismic studies, computer simulations, risk assessments, and logistical planning. The findings, expected by the end of 2025, will determine whether CO_2 injection trials can begin in 2026, provided that the necessary funding and permitting for this implementation phase are secured.

While domestic storage offers advantages such as reduced transportation distances, thus lowering costs and environmental impacts, as well as enhanced political and social acceptance through local problem-solving and energy independence, challenges persist. Public resistance, often framed as "not in my backyard" objections, could hinder progress, and the development of storage sites and of the associated infrastructure – if possible - will take significant time. Additionally, uncertainties about Switzerland's storage capacity mean that CO_2 exports for storage abroad may be necessary in the interim, requiring the establishment of a robust transport network. The CITru project provides an essential opportunity to generate insights into the technical, regulatory, and societal dimensions of CO_2 storage in Switzerland, paving the way for potential commercial-scale projects in the future.

Currently, underground CO_2 storage sites are being developed primarily in the North Sea, with the largest share of them located in Norway, in Denmark, in the UK or in Iceland (e.g., Northern Lights storage site or Carbfix Coda Terminal) [2] and already offer the possibility of storing CO_2 from European emitters, although not yet commercially. Around Switzerland, further sites have been announced in the Netherlands and in Italy to be operational before 2030, as well as in France. While in Europe the storage sites of Sleipner and Snøhvit are in operation since 1996 and 2008, respectively, these sites are exclusively dedicated to store CO_2 produced from natural gas extraction. Numerous

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[2] https://www.sintef.no/projectweb/elegancy/
[3] https://citru.ethz.ch/de/home/

storage sites are currently under development or in construction and are planned to start operation in the upcoming years.

The advantage of foreign storage sites resides in their ability to allow for a rapid deployment of CCTS chains as they are or will soon be operational. Depending on the actual capacity for CO_2 storage in the Swiss underground, it may be unavoidable to export part of the Swiss emissions in any case. In this regard, it would be important for Swiss emitters to secure enough storage capacity abroad, as some sites may primarily be used for domestic emissions. In recent years, Switzerland has intended to establish bilateral agreements with countries proposing CO_2 storage capacity: among them, a declaration of intent with Norway [3], a joint declaration of intent with Iceland [4], and memoranda of understanding with Sweden [5] and the Netherlands [6]. As a land-locked country, Switzerland requires a transport network such that the CO_2 can be transported to the coast and access maritime transport [7-9]. However, a country-wide transport network would also be needed in the case of domestic storage. Finally, the export of Swiss CO_2 emissions may be challenged by public acceptance, which disapproves projects to reduce emissions abroad [10].

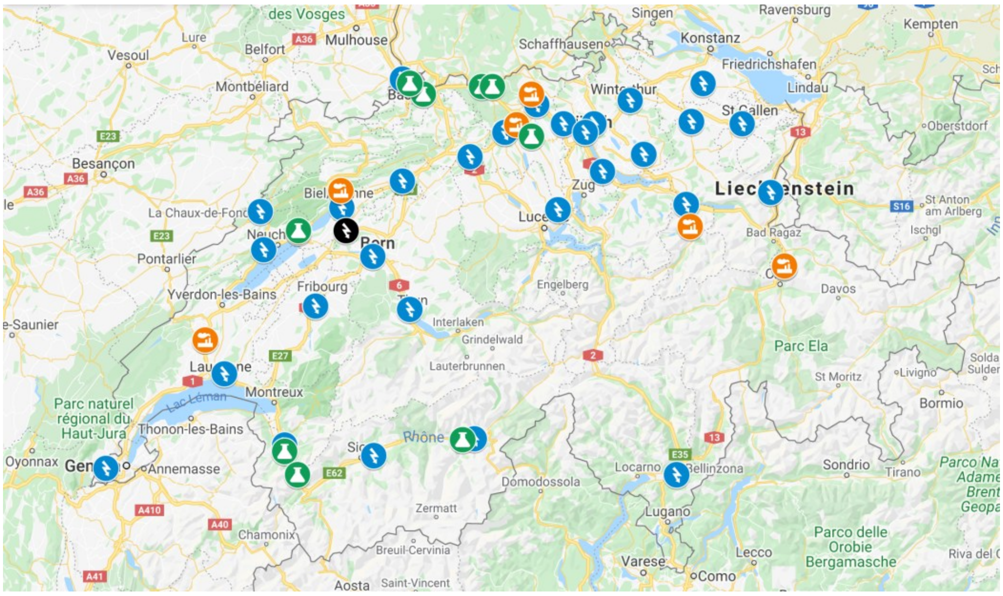

Figure 1. Geographical distribution of large-scale Swiss CO_2 emitters: Waste-to-Energy plants emitting ca. 4.5 $MtCO_2/y$ (in blue), cement manufacturing plants emitting ca. 2.6 $MtCO_2/y$ (in orange), and chemical plants emitting ca. 1.1 $MtCO_2/y$ (in green). Note: Emissions data refer to the year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

The geographical distribution of the ca. 40 large-scale Swiss CO_2 emitters (Figure 1) and the need to collect the captured CO_2 and transport it to locations where it is permanently stored make a CO_2 transport network necessary in Switzerland and 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 to explore the feasibility of such an international CCTS solution, we aim with this WP 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 solutions.

The geological site considered is in Iceland, developed by Carbfix, whose technology imitates and accelerates natural processes of carbon removal. Carbfix dissolves CO_2 in water and injects deep into the subsurface where it has been seen to form minerals in under two years [11,12]. The process involves dissolving the gases in water prior or during injection. Once dissolved, the gases are no longer buoyant, improving considerably the security of the injection and making the need for a cap rock obsolete.

Carbfix operations at industry scale started in 2014 at Hellisheiði with the installation of a permanent capture plant to reduce CO_2 and H_2S emissions from the Hellisheiði geothermal power plant. CO_2 and H_2S emissions are separated from the other non-condensable gases in the emissions stream and captured by water dissolution. The gas charged water is then transported under pressure to an injection well where it is co-injected with geothermal brine from the power station into a fractured basaltic reservoir. This injection has been part of the operations of the geothermal power plant since 2014. This capture plant represents approximately ~12,000 tonnes annually along with 6000 tonnes of H_2S. Preparation work is currently underway to increase capture and injection to 95% of the CO_2 from the power station in 2025. The gas-charged fluid from the capture plant is co-injected with geothermal brine from the power station to a depth of ~800 m into the basaltic reservoir at Hellisheiði. These wells are specifically retrofitted to receive the gas-charged water from Carbfix with a stainless-steel pipes and casing as the gas-charged water is acidic and corrosive to carbon steel that is used for well casings. The fate of the injected gases is then monitored closely by using tracers and by following geochemical signal by sampling fluids in designated monitoring wells in the vicinity of the injection point. Measured tracer concentration in monitoring wells and mass balance calculations enable evaluation of CO_2 mineralization. Additionally, Carbfix is injecting CO_2 from two direct air capture (DAC) plants that were designed and installed by the Swiss company Climeworks in Hellisheiði that will have a combined nominal capturing capacity of ca. 40,000 tonnes of CO_2 every year.

1.2 Purpose of the WP

This WP aims 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 to demonstrate 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 from upgrading biogas produced at the wastewater treatment plant. Neustark and Ara Region Bern manage and operate the liquefaction unit installed at the emitter's facilities and load the CO_2 onto dedicated iso-containers for transport. Salzmann AG Transporte and SBB Cargo/ChemOil transport 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 by rail to the port of Rotterdam. The sea freight from the port of Rotterdam to Reykjavik is managed by the service provider Samskip and is overseen by ChemOil and Carbfix. The transported CO_2 is then dissolved in water and injected, or co-inected with water and mixed at a given depth in the underground, for permanent mineral storage in a basalt rock formation that serves as a storage reservoir. Tests with freshwater are carried out at the Hellisheidi site, while tests using seawater are conducted at the Helguvík site. Carbfix is in charge (i) of the technical and geological characterization of the injection 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 work (i) provides a blueprint design for CO_2 supply chains that will be developed in the future, (ii) proves the feasibility of such chains, and (iii) allows early identification of techno-economic, regulatory, and environmental hurdles 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[4], and to the Icelandic project CO_2SeaStone[5]. While CO_2SeaStone covers the activities led by Carbfix regarding CO_2 injection and geochemical monitoring, the companion project DemoUpStorage (with

[4] https://www.aramis.admin.ch/Texte/?ProjectID=50768
[5] https://www.carbfix.com/co2-seastone

principal investigator ETH Prof. Stefan Wiemer), also partially funded and supported by the SFOE and by the FOEN in 2022, uses novel, dense, and combined geophysical and geochemical monitoring techniques to track the migration of the CO_2 when injected into basalts and its subsequent mineralization, while complementing the interpretation of the data through laboratory experiments and numerical modelling.

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 of Swiss CO_2 dissolved in seawater in subsurface basalt rock formation at the pilot scale. The assessment of its mineralization performance is addressed in the DemoUpStorage project.
- To assess the overall techno-economic and environmental (including life-cycle assessment) performance of the full CCTS supply chain and to identify barriers and challenges to the implementation of future CO_2 value chains.Description of facility

2 The CCTS supply chain

The CCTS supply chain consists of four steps: 1) liquefaction of CO_2 and loading of the iso-containers in Switzerland, 2) transport of the iso-containers by truck, train, and ship to the injection site, 3) injection of CO_2 for permanent storage in Iceland, and 4) return of the iso-containers to Switzerland.

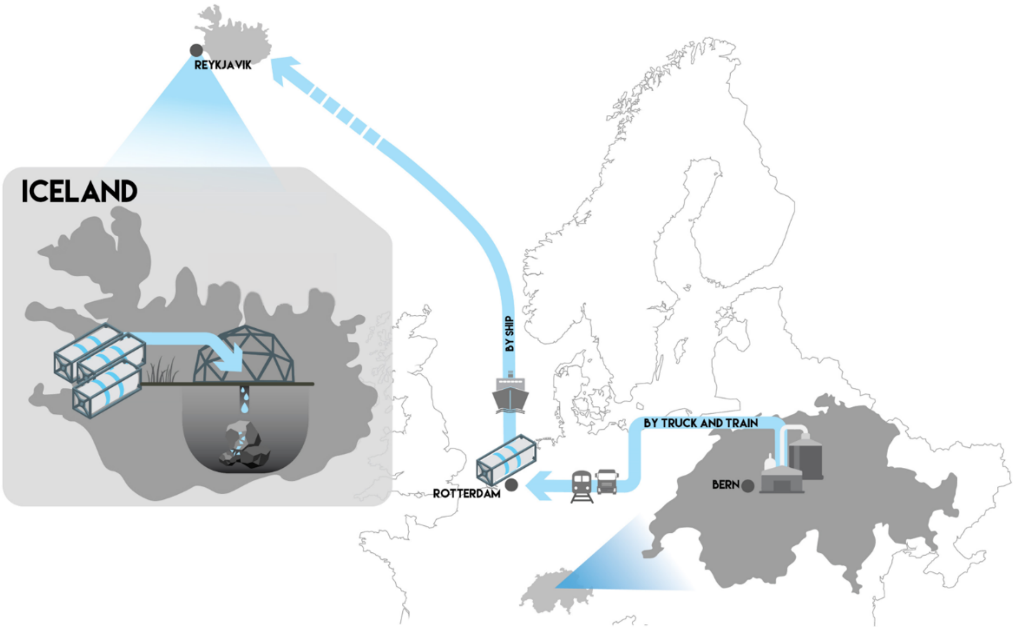

Figure 2. Carbon capture, transport and storage supply chain, including: Liquefaction of CO_2 and loading of the iso-containers in Switzerland, transport of iso-containers by truck, train, and ship, and injection of CO_2 for permanent storage in Iceland. The iso-containers need to be transported back to Switzerland for further transport of CO_2.

The four steps of the CCTS supply chain are described in detail below.

Liquefaction of CO_2 at Ara Region Bern and loading of the iso-containers

Figure 3. Iso-container for CO_2 transport.

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 the plant itself (same CO_2 source as in WP2). The liquefaction unit, operated by Neustark, dries, compresses and finally cools the CO_2 so that 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 vacuum-insulated iso-containers have a holding time of 64 to 187 days (as indicated by the manufacturer). Each iso-container has a capacity of ca. 20 tons of 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.

Transport of iso-containers from Ara Bern to the injection site in Iceland

- 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 107 km and the truck transporting the iso-container uses biogas as fuel.
- Train-based transport from Weil-am-Rhein to Rotterdam. In Weil-am-Rhein the iso-containers are cleared through customs and are loaded onto rail (managed by ChemOil, as subsidiary of SBB Cargo). 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 approximately 2150 km, and the travel time is approximately six days depending on 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

After the offloading of the CO_2 in Iceland, empty iso-containers are returned to Switzerland via the same transport chain in the opposite direction.

2.1 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 5. Location oft he Helguvík injection site.

2.1.1 Helguvík injection site

For the first time, tests of injection of CO_2 dissolved in seawater have been conducted at the pilot scale. The selected storage site for the CO_2 has been identified in Helguvík, see Figure 5. Helguvík site preparations prior to injection of CO_2 included a geological characterization of the injection site. The work involved the review of existing data, sampling of reservoir fluids and rocks, mapping of geological characteristics of the injection site including the properties of surface rocks and the mapping of potential structures in the vicinity of the injection as well. This work was done to prepare for the demonstrations and collect data to predict the chemical response of the CO_2-seawater reservoir rock interaction as well as establishing a baseline prior to injection. Furthermore, rock samples were collected for further characterization and experimental work on a laboratory scale to demonstrate the feasibility of CO_2-seawater injection. This allows for in-depth analysis of the evolution of the permeability of the reservoir rocks during the CO_2-seawater injection and subsequent mineralization by simulating the in-situ reservoir conditions.

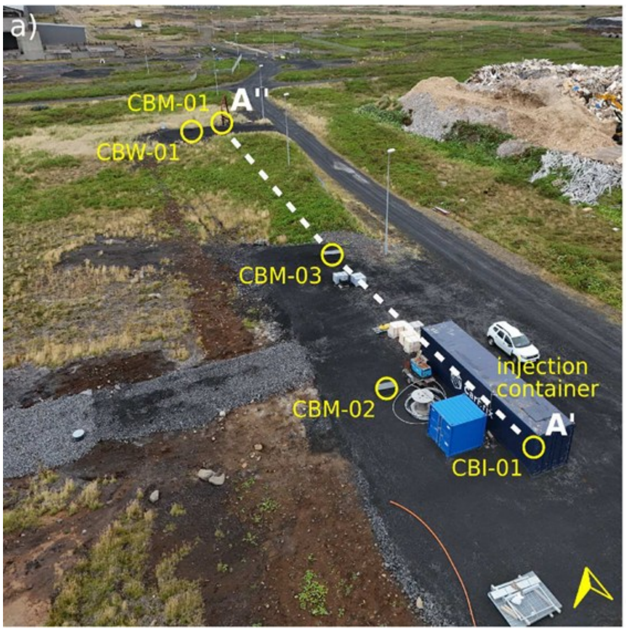

Figure 6. Overview of the Helguvík injection and storage site. Source: DemoUpStorage.

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. For the project, an injection well (CBI-01), a sea water sourcing well (CBW-01) and three monitoring wells (CBM-01, CBM-02 and CBM-03) were drilled by the drilling company Alvarr ehf, see Figure 6. Drilling began in October 2022 with the drilling of CBI-01, that had to be temporarily abandoned and then later revisited for further drilling. CBI-01 was then also the last well to be finished in June 2023. Drilling took longer than anticipated due to various difficulties regarding the drilling equipment and a long period of below freezing temperatures.

CBI-01 is the injection well upon which the Carbfix mobile injection unit is placed. The well depth is 420 m with casing reaching 249 m, which is followed by an open hole section. CBM-01 and CBM-03 are monitoring wells, one of which will be used for geochemical measurements and the other for geophysical measurements. These wells are both drilled to around 400m with casing to around 130m. CBM-02 is a shallow monitoring well and is used to detect any potential fugitive emissions from the reservoir. CBW-01 originally was drilled to 50 meters and later deepened to 115 meters.

Figure 7. Carbfix mobile injection unit located at Helguvik.

Figure 8. Inside of the mobile injection unit, injection well.

The Carbfix mobile injection unit was constructed for the project, and the site layout including placement of all wells, pipes and cables was specified, see Figure 7 and Figure 8. This involved a redesign of the previous Carbfix injection system to fit into a single 40 feet container. The container was constructed offsite and subsequently installed on top of the injection well CBI-01.

The container is also used to house a mixing apparatus to add tracers, and a portable mass spectrometer, the miniRUEDI, used to quantify the partial pressures of different gas species (results obtained through the miniRuedi system are reported in the DemoUpStorage report). Seawater is then supplied by a submersible pump placed in well CBW-01. This is the first demonstration of the Carbfix mobile injection unit and may open new doors in terms of pilot injections of this type. In fact, future reservoirs can be tested with the Carbfix mobile injection unit without the need for the construction of an injection system on site.
CO_2 and seawater has been injected into the injection well via separate pipes (see Figure 8), down to about 250-300 m depth, where the CO_2 and the seawater has been mixed at a pre-determined mixing point and transferred through an inner mixing pipe within the well. The pressure down-hole ensures complete dissolution of CO_2 before entering the storage formation, and thus achieving instant solubility trapping.The injection system's design is based on a demonstrated and proven technology developed by Carbfix. The injection parameters are continuously monitored enabling accurate evaluation and quantification of the injection.

2.1.2 Hellisheiði injection site

As the drilling of Helguvík wells took longer than anticipated, the project partners decided to inject the CO_2 from the first four containers shipped to Iceland into well HN-14 in Hellisheiði. Well HN-14 is one of the two injection wells used for the CO_2 from the Hellisheiði power plant [12].

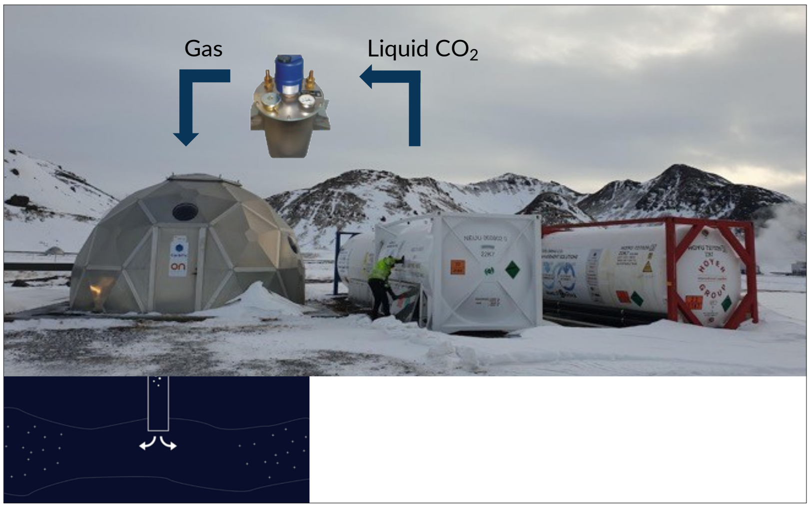

Figure 9. Schematic representation of the injection process at the Hellisheiði site.

Pre-test injection of CO_2 using freshwater has been conducted at the existing Carbfix well on the premises of its sister's company, ON Power Hellisheiði geothermal power plant. Larger-scale injections in Hellisheiði have been ongoing since 2014 with approximately 12,000 t of CO_2 from the geothermal plant injected annually. At the Hellisheiði geothermal power plant, CO_2 is dissolved in water and injected into subsurface basalts at approximately 800 m depth, where the CO_2 reacts with the basaltic rocks to form stable carbonates at around 250 °C. Measurements of dissolved inorganic carbon in monitoring wells indicate that more than half of the injected CO_2 is fixed in carbonates within a few months of injection [13].

Within the scope of this project, liquid CO_2 from the iso-containers is first vaporized in a heat exchanger. An evaporator was installed next to the wellhead and connected to the stainless-steel pipe transporting gas-charged water into the injection well. Liquid CO_2 was then fed into this evaporator, and gaseous CO_2 was diverted into the injection well. The flow rate of this additional CO_2 constituted a small portion (approximately 0.5-1 ton/day) of the CO_2 from the power plant (approximately 33 t/day) and thus had minimum impact on the operation of the injection system. Gaseous CO_2 is then dissolved in freshwater and injected in the Carbfix injection well HN-14 (see Figure 9). Further details on the motivation and background of these tests are provided in Section 4.

3 Procedures and methodology

Data and measurements have been collected and evaluated to assess the techno-economic and environmental performance of the CCTS chain during the demonstration. Furthermore, a monitoring concept has been established to collect all data and measurements. Finally, a rigorous life-cycle assessment has been carried out to determine the environmental impact following procedures defined in ISO 14040.

3.1 Key-performance indicators

The performance assessment of the CCTS chain is based on the key-performance indicators (KPIs) below. The KPIs aim to establish comparability of the CCTS chain with future projects in terms of techno-economic and environmental performance and hence, include relative indicators (e.g., per ton of CO_2 stored or per iso-container) for costs and greenhouse gas avoidance in addition to total indicators. We report both carbon dioxide stored, life-cycle greenhouse gas emission avoided, and net carbon dioxide removal separately for transparency. Additional indicators provide insights into the individual steps of the CCTS chain, in particular the transport step.

- Techno-economic
  - Total cost, costs per transport segment and average cost per ton of CO_2 transported (CHF and CHF/tCO_2);
  - CO_2 loading (mass of CO_2 per iso-container, t_{CO2}/shipment);
- Environmental
  - Net greenhouse gas emissions reduced over the life cycle of the CCTS chain ($t_{CO2\text{-}eq.}$), CO_2 captured and processed (t_{CO2}), and resulting life-cycle greenhouse gas emission reduction efficiency (%);
  - Environmental KPIs based on the Environmental Footprint 3.0 (Table 2);

3.2 Monitoring concepts and measurements and data collection

A monitoring concept has been established to measure key quantities during the operation of the CCTS chain to assess its performance. The monitoring concept 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. Accurate monitoring of the incurred costs;
2. Assessing the timing and logistics;
3. Determining how much CO_2 is captured, transported, and injected, and estimating possible losses along the way;
4. Refining the LCA model with primary data.

An overview of measurements and data to be collected is provided in Figure 10. Details regarding the quantities measured, the points of measurement along the pilot CCTS chain and the relation to the objectives are provided in Table 1. Overall, the types of data that are collected can be broadly

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

categorized in:

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

Measured data for each shipment of the iso-containers is collected in a database to allow for comparative analysis of all the shipments.

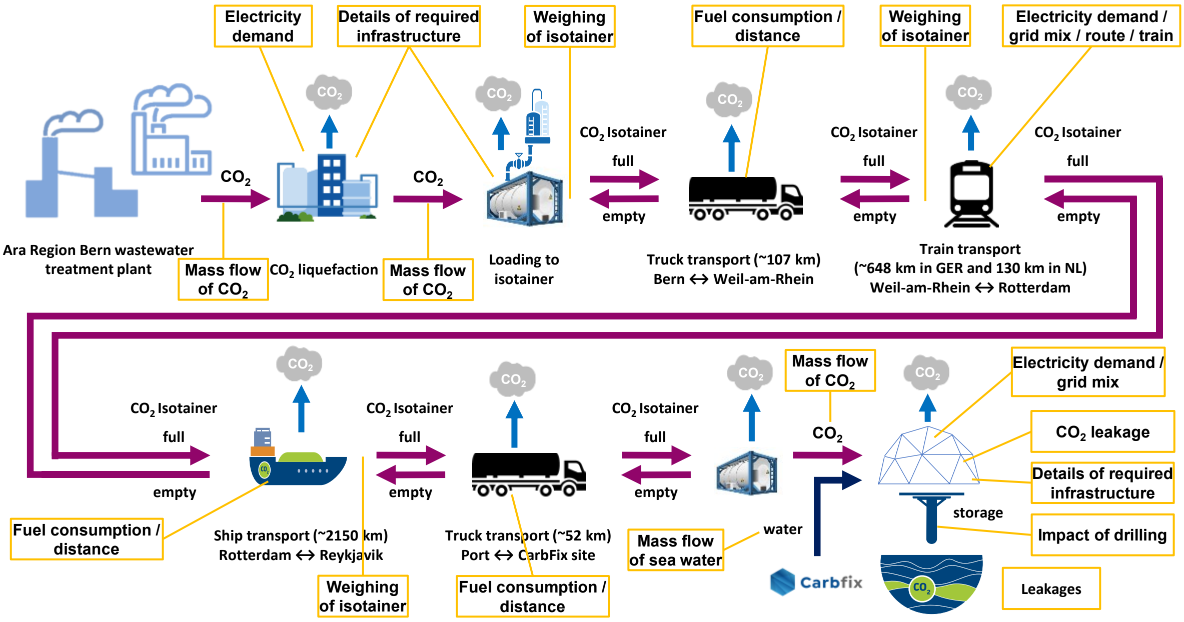

Figure 10. Overview of measurements and data collection upon the demonstration CCTS supply chain.

Table 1: Measurements and data collection in the demonstration chain and relation to 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 traveled	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 controll…)	electricity consumed	kWh	relevant local grid mix	X					X				X
Fuel consumption for transport	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 des-cription; 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 <u>costs</u> are retrieved from project partners or service providers, through e.g., invoices;

- Data related to the schedule and timing of the various steps of the CCTS supply chain are requested from project partners.
- 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 for trucks 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;
  - CO_2 transport:
    - Type of fuel, consumption, distance traveled
    - Distance traveled, electricity consumption, grid mix
    - Distance traveled for ships;
    - Type of fuel, consumption, distance traveled of truck in Iceland;
  - CO_2 injection:
    - Electricity consumption for seawater pump, CO_2 pump, process control;
    - Infrastructure requirements (pumps, piping, process control).

3.3 Technoeconomic reporting

A technoeconomic reporting of the CCTS supply chain has been carried out based on the expenditure incurred in the project. It is worth mentioning that given the pilot nature of the project and the fact that this is a first-of-a-kind demonstration, a rigorous economic assessment would not be a representative cost indicator for this technology when further developed and deployed on a larger scale; hence this is not performed. Nonetheless, we report openly all the items associated with costs incurred for the demonstration.

In the following, we list the cost items related to the supply and transport of the CO_2:

- CO_2 supply costs (CHF/tCO2); this cost is a flat rate that covers expenditures related to CO_2 sourcing (capture, liquefaction and handling).
- Isotainer rental (CHF/month/isotainer) and chassis rental (CHF/month/chassis); these costs are paid per unit time for the rental of each container, regardless of the number of roundtrips performed, and for the rental of the chassis for the truck transport of the isotainers in Switzerland.

- Truck transport costs (CHF/roundtrip/isotainer); this cost covers the expenses for each loaded isotainer delivery from Ara Bern to Weil am Rhein, and for the return transport of the empty isotainer (i.e., service price).
- Train transport costs (CHF/roundtrip/isotainer); this cost covers the expenses for each loaded isotainer delivery from Weil am Rhein to Rotterdam, and for the return transport of the empty isotainer (i.e., service price).
- Ship transport costs (CHF/roundtrip/isotainer); this cost covers the expenses for each loaded isotainer delivery from Rotterdam to the injection site, and for the return transport of the empty isotainer (i.e., service price). It includes the ship transport between Rotterdam and Reykjavik, and transport via truck to the injection site.

3.4 Life-cycle assessment

A life-cycle assessment is performed to evaluate the environmental performance of the CCTS supply chain. In particular, we consider the conditioning of CO_2 captured at Ara Bern in Switzerland, the multimodal transport of the CO_2 from Switzerland to Iceland, and injection at a dedicated geological storage by Carbfix in Helguvík, Iceland. The environmental assessment considers the full life-cycle of the CCTS supply chain from cradle to grave, including resource extraction, production, transportation, use, and end-of-life (Figure 11, left). The LCA adopts an iterative approach following ISO 14040 [14] (Figure 11, right).

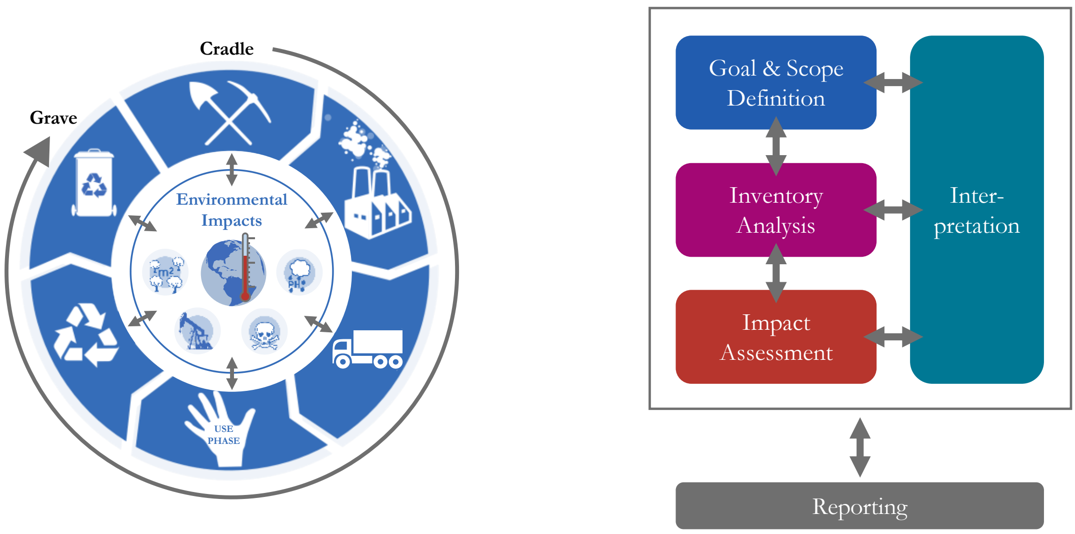

Figure 11: Life Cycle Assessment (LCA): Evaluation of environmental impacts of the entire life cycle from cradle to grave (left). The relation of the four steps in LCA according to ISO 14040 (right).

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 carried out in an identical manner in both LCAs to ensure consistency.

Goal & Scope Definition

The LCA of the CCTS supply chain outlined in Section □ assesses the environmental impacts of the supply chain over its entire life cycle. A key output of the analysis is the evaluation of the net-negative greenhouse emissions of the overall chain, i.e., the net amount of CO_2 removed from the atmosphere and permanently stored, considering the greenhouse gas emissions caused by the life cycle of the supply chain. In addition, the LCA assesses a wide range of environmental impact categories to identify potential burden shifting and to quantify contributions of CCTS supply chain steps to other environmental impact categories.

The geographic distance between the CO_2 point source in Switzerland and the permanent storage site in Iceland implies the need for CO_2 transport and, in turn, the conditioning of CO_2 into a state suitable for transport. The system boundaries of the LCA include the handling of the CO_2 within the CCTS supply chain demonstrator after the separation of the CO_2 at Ara Bern, including CO_2 liquefaction, transport, and geological storage (Figure 12).

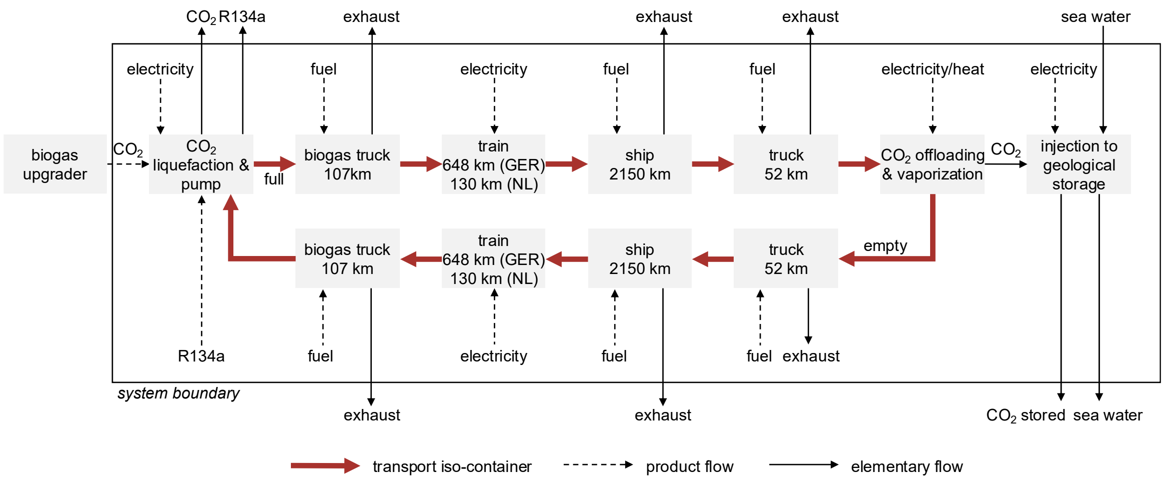

Figure 12: System boundary and streams for LCA of demonstration chain.

The results of the LCA provide insights into the environmental performance of the demonstrator chain to inform the members of the DemoUpCARMA consortium, the federal offices, SFOE and FOEN, the CCTS community, and the general public about the environmental benefits and challenges of CCTS supply chains. As the goal of WP3 is the demonstration of transport and permanent storage of Swiss biogenic CO_2, the function of the CCTS chain is the permanent geological storage of CO_2 by in Iceland that is separated in Switzerland. This work considers handling 1 t of captured CO_2 as the reference flow.

The background processes are modeled using aggregated datasets from *ecoinvent 3.8 (cut-off)* [15]. In general, we apply country-specific processes from ecoinvent to reflect the multi-national nature of the CCTS supply chain. We resort to averaged European and global processes if required due to a lack of data.

CCTS supply chains are applied to reduce the climate change impact but may result in burden-shifting to other impact categories. To gain insights into burden-shifting, we assess the environmental impact in the categories of the *Environmental Footprint 3.0* (EF 3.0) methodology [16]. An overview of the impact categories considered can be found in Table 2.

Table 2: Impact categories assessed in the LCA based on *Environmental Footprint 3.0* [16] Recommendation levels: recommended and satisfactory (I), recommended but in need of some improvement (II), recommended but to be applied with caution (III).

Impact category	Unit	Recommendation level
Climate Change	kg CO_2 eq.	I
Ozone depletion	kg CFC-11 eq.	I
Respiratory inorganics	Disease incidences	I
Ionizing radiation	kBq U235 eq.	II
Photochemical ozone formation	kg NMVOC eq.	II
Acidification	mol of H+ eq.	II
Eutrophication terrestrial	mol of N eq.	II
Eutrophication freshwater	kg P eq.	II
Eutrophication marine	kg N eq.	II
Human health effects, cancer	CTUh	III
Human health effects, none-cancer	CTUh	III
Ecotoxicity freshwater	CTUe	III
Land use	soil quality index	III
Water use	m3 world eq. deprived	III
Resource use, mineral and metals	kg Sb eq.	III
Resource use, energy carriers	MJ	III

In accordance with EF 3.0, biogenic carbon streams are assumed to have zero impacts. The combustion of fossil fuels, e.g., to supply heat using natural gas, results in fossil GHG emissions. This is not the case for bio-based fuels like biogas. However, the combustion of bio-based fuels still results in climate change impact due to land-use change, cultivation, harvest, transport, and processing [17] or due to the emission of molecules with high global warming potential, e.g., biomethane or molecules formed in the combustion gases. In addition to EF 3.0, the environmental impacts are evaluated based on the ecological scarcity method 2013 [18] in Appendix 11.2.

The LCA for DemoUpCARMA is conducted with the open-source software *Brightway2* [19] and the *Activity Browser* [20].

3.5 Key regulatory gaps

Key regulatory gaps from the two pilot and demonstration projects in WP2, demonstration of CO_2 utilization and storage in concrete, and WP3, demonstration of cross-border CO_2 transport and geological storage, have been identified through the project. Regulatory challenges from the pilot phase have been gathered to collect learnings and potential solutions for future scale-up of carbon capture, utilization, and storage (CCUS), as well as CCTS projects. To address this subtask, we regularly exchanged with the relevant project partners Ara Region Bern, Carbfix, EMPA, Kästli Bau AG, Neustark, SBB Cargo and Salzmann Transporte.

For the purposes of this report, key regulatory gaps refer to areas where laws, regulations or standards relating to technical and environmental aspects are insufficient, unclear, obstructive or entirely absent and therefore pose gaps or challenges for the two pilot and demonstration projects as well as for potential future initiatives on a larger scale. The key regulatory gaps identified within this WP do not refer to financial and organizational aspects.

In April 2022, we involved the relevant project partners participating in WP2 and WP3 for the first time to coordinate the objectives of this assessment and establish a process for the ongoing collection of key regulatory gaps and learnings. Following the shipment of the first isotainer with CO_2 to Iceland in August 2022, as part of the WP3, we held an initial series of exchanges in October 2022 to gather early experiences. Until the planned end of the project in October 2023, we initiated regular, biannual exchanges with the respective project partners. Since the completion of WP3 was postponed, we held a final exchange round for WP3 in October 2024, while also conducting an additional round for WP2. Depending on the level of detail provided, we worked closely with the partners to solve and prioritize these gaps, focusing on the most critical ones in our results and discussion.

As a further step, we conducted desk research on the collected key regulatory gaps and learnings and complemented our findings with existing literature or outcomes from other reports. In addition, we included further relevant considerations that came up during our research, even if they did not directly relate to the key regulatory gaps we defined. By including these considerations, we aim to cover key regulatory gaps and share all significant insights we discovered. Finally, based on our findings, we aimed to derive overarching conclusions and insights that could be useful not only for the pilot and demonstration projects in WP2 and WP3 but also for larger-scale commercial projects or other similar initiatives in the future.

Due to the novelty of these projects and the partial lack of regulatory frameworks for the projects in WP2 and WP3, the results of this work mainly aim to provide a first overview of key regulatory aspects to focus on in the future continuation of the projects and serve as a foundation for further in-depth analyses.

4 Results and discussion

4.1 Demonstration results and evaluation

4.1.1 CO_2 cross-border shipments

Cross-border shipments of CO_2 started in 2022 for injection pre-tests into existing Carbfix wells at the Hellisheiði geothermal power plant using freshwater. The schedule of the first shipment is illustrated schematically in Figure 13. The injection pre-tests aim to de-risk the seawater injection at Helguvík and the transport itself by revealing obstacles and challenges to the CCTS supply chain. In summer 2022, four CO_2 shipments have been made to Iceland.

The pre-tests revealed a lack of clarity on the classification of CO_2 as a chemical product or a waste. The lack of clarity was overcome by the Icelandic Environmental Protection Agency by exempting the transported CO_2 from Icelandic waste regulations as part of a research project.

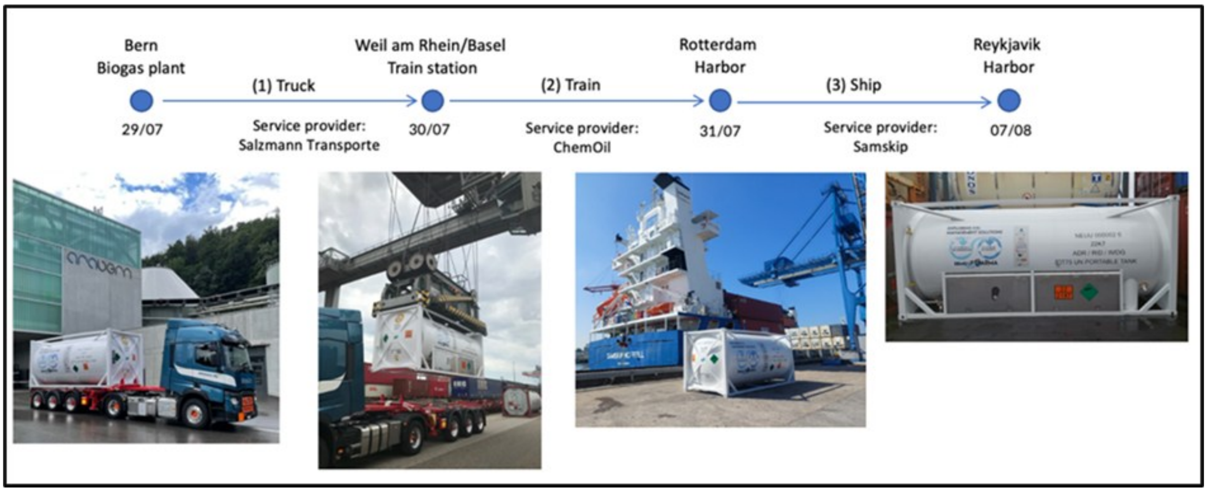

Figure 13. Schedule of the first shipment of the CCTS supply chain.

Furthermore, the pre-tests initiated bilateral discussions between the Agency and the Industrial Waste Section at FOEN. The latter has informed Neustark (as the CO_2 supplier) on September 15th, 2022 that:

- In Switzerland, according to Art. 7 (6) of the Environmental Protection Act (USG), waste is movable property that 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 as well as 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 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* must be issued by the FOEN (which does not need the involvement nor the approval of the Icelandic authority).

After this communication, further shipments of CO_2 from Switzerland to Iceland were put on idle. In the meantime, Neustark applied for the Unilateral export permit, which was granted in Summer 2023. Despite the permit was granted, further delays were caused by misalignment between international regulations concerning the transport of CO_2 labelled as waste material. Ultimately, in October 2023, the first CO_2-loaded isocontainer was successfully delivered to Iceland compliant with the granted Unilateral export permit.

A total of 15 shipments have been sent to Iceland, split between Hellisheiði and Helguvík sites. Of these, 13 containers have been returned, while two remain in Iceland fully loaded, awaiting injection (as of September 2025).

4.1.2 CO_2 injection at Hellisheiði

For the pre-tests of CO_2 injection at Hellisheiði, a CO_2 evaporator and fittings were procured, and adaptations to the injection system were made. CO_2 injection started on November 4th, 2022. The CO_2 from three iso-containers was injected, for a total of ca. 50 tons.

4.1.3 CO_2 shipments to Helguvík

In total, 11 shipments of CO_2-isocontainers from Ara Bern to the Carbfix injection site in Helguvík took place between September 27, 2023 and August 7, 2024. In total, approximately 210 t of liquified CO_2 were loaded into isocontainers at Ara Bern and shipped to the dedicated injection site at Helguvík. There, approximately 142 t of CO_2 were unloaded to be injected into the storage well until September 2024. As of September 2025, 2 additional shipments of approximately 18 t each need to be injected. Further, the intermediary storage tank still held 17.5 t of CO_2. The mass difference between loaded CO_2 and expected CO_2 injected upon completion of the demonstration is approximately 14.5 t and can be attributed to measurement accuracy and operational inefficiencies:

- The first-ever injection with seawater required initial learning to improve the injection process, such as selecting appropriate hose sizes or managing pressures in the intermediary CO_2 storage tanks. The initial learning in the demonstration resulted in some losses of CO_2.
- About 2-3 % of the loaded CO_2 is estimated to remain in the isocontainers bound for the return trip as residual CO_2 after unloading, reducing the amount of CO_2 injected.
- The scheduling of the return shipments and space limitations in the intermediary storage tank resulted in the incomplete unloading of 1.5 t of CO_2 from one isocontainer.
- The mass measurement of unloaded CO_2 is partially based on analog meters installed at the isocontainers, limiting measurement accuracy.

Furthermore, the initial transport plan for the CO_2 iso-containers, which aimed for a regular 5-week round-trip schedule, faced significant challenges. For instance, during summer 2024, a series of issues disrupted operations. One of the deliveries had to be postponed due to a breakdown in the liquefaction unit. Additionally, railway construction work in August caused a three-week delay in transport. As of September 2024, around 60 tons of CO_2, delivered in July and August, remained in Iceland and have not yet been injected due to ongoing problems at the Carbfix site. These included issues with both the monitoring well and the injection well, further delaying injection activities. While only about 10 tons may have been injected in July and August, the majority of CO_2 is still awaiting processing.

Due to these operational challenges, the initial plan of sending up to 500-1000 tons of CO_2, with one container every week, was not achieved. The various inefficiencies and limitations have prevented the planned shipment frequency and injection volume from being achieved.

Table 3: Shipments of CO_2-isocontainers from Ara Bern to the Carbfix injection site in Helguvík until September 2025.

Shipment	Date	CO_2 loaded, Ara Bern	CO_2 injected, Carbfix, Helguvík	Comments
1	September 27, 2023	17.5 t	9 t	long storage duration of CO_2 in isocontainer resulted in overpressure that was vented
2	November 17, 2023	19 t	18 t	
3	March 1, 2024	19.5 t	17 t	
4	March 18, 2024	19.5 t	16 t	
5	April 23, 2024	19.5 t	19 t	
6	May 21, 2024	19.5 t	16 t	

7	June 18, 2024	19.5t	16 t	
8	July 2, 2024	19.5	16 t	
9	July 19, 2024	19.5 t	15 t	temporary storage full, CO_2 not fully unloaded
10	July 26, 2024	17.7 t		not yet unloaded as of September 2025
11	August 7, 2024	19.4 t		not yet unloaded as of September 2025
Total		210.1 t	142 t	

4.1.4 CO_2 injection at Helguvík

The original proposed test site for the project was at Miðnesheiði using the well RH-03. The well is a so-called heat gradient well and is owned by HS-Veitur, which had generously shared access to the well. During the preparation phase, drilling reports, well logs and geological reports were inspected. Water samples were collected with submersible pump to establish the geochemical baseline of the reservoir fluids.

Figure 14. Picture of the Helguvík injection site in preparation, Summer 2022.

At the onset of the project, Carbfix had also been corresponding with the municipality Reykjanesbær to secure a land plot to establish an injection site near utilities access (i.e., water and electricity) and the harbour of Helguvík. Part of this correspondence included securing access to an existing well HV-01 at an abandoned industrial plot. This well was drilled as a water supply for aquaculture and Carbfix considered this as a potential monitoring well for the project. However, during the design phase, the site near HV-01 was not considered feasible due to distance to infrastructure.

In spring 2022, Carbfix managed to secure a plot on lease from Reykjanesbær. Thus, a decision to move the demonstration site from Miðnesheiði to Helguvík was taken, motivated by the fact that this new site could (i) accommodate larger CO_2 quantities in view of a scale-up project, and (ii) enable a more effective and accurate monitoring system of the CO_2 injection.

The move of the injection site resulted in challenges in harmonizing the design for the injection and monitoring wells, resulting in a new arrangement of wells and time delays. The construction of the injection site in Helguvík started on August 29th, 2022 (Figure 14). Drilling was completed in June 2023, with the completion of the injection well, the seawater sourcing well, and three monitoring wells. Following the completion, site preparations began. These preparations involved transporting a mobile injection system to Helguvík and connecting it to the facilities on site, installing a temporary CO_2 storage tank, commissioning the system and a general clean up on site following drilling. On October 27, 2023, the first injection of a few kg of CO_2 dissolved in seawater was carried out, marking a significant milestone for the project. This event also represented the first injection of its kind globally. Post-initial injection efforts concentrated on further setup, programming, and testing of the controlling system. During this period around 300kg of CO_2 were injected. In December 2023, a decision was made to move and reconstruct the existing tracer system from inside the container to the outside to prevent cross contamination related to sampling and ensure robustness of the system.

An intermittent injection of CO_2 from Switzerland began on the 15th of January 2024 and has continued throughout the period. By September 1st, 2024, a total of 136 t of CO_2 had been injected at an average rate of ca.4 t/week. Since that time, injections have been suspended due to technical challenges at the site that required resolution. At present, work is underway to prepare the site for future commercial operations, and these preparations are now in their final stages.

As expected with a new system the operation faced some challenges during the project period, namely:

- The delivery of the CO_2 evaporator was delayed significantly due to shipping delays and warehouse errors. Therefore, Carbfix installed a temporary evaporator that had been used previously at Hellisheiði to inject the first four delivered containers of CO_2. This evaporator was not powerful enough to operate the injection system at Helguvík at optimal capacity resulting in less CO_2 injected than previously anticipated. The correctly specified evaporator was installed in March 2024.
- Initially, the CO_2 transportation chain was not fully aligned with the system's injection capacity, resulting in intermittent periods of reduced CO_2 availability for injection. Noticeable downtime occurred in early spring and late summer due to supply disruptions. During the summer of 2024, several transport-related issues compounded these difficulties. A delivery had to be postponed because of a malfunction in the liquefaction unit. Additionally, railway construction in August caused delays for three weeks, further disrupting the logistics chain. Consequently, 60 tons of CO_2 delivered to Iceland in July and August remain un-injected due to operational challenges at the injection site. Both containers are currently on site and awaiting injection, which will commence once the remaining site works have been completed.
- In February 2024, the injection was stopped for a couple of days due to an electricity shortage caused by a volcanic eruption at Reykjanes.
- Various system updates and tests needed throughout the period for a better in-depth monitoring of the system and of the injection process. This included changing the water to gas ratio, testing the system at various injection flows and adding more measured parameters to the control system.

Prior to the start of CO_2 injection, a geochemical baseline was established which was then followed by geochemical monitoring once regular injections started. Geochemical monitoring included sampling of the injection sea water and water from all the wells in the vicinity of the injection well which were then analyzed and any changes monitored. *4*

4.2 Techno-economic reporting

An overview of the costs incurred is shown schematically in Table 5, which includes the expenses associated with 15 shipments and the rental of 5 isotainers. Considering that the total amount of CO_2 transported was ca. 260 tons, this results in an average sourcing and transport cost of 1600 CHF per ton CO_2 transported.

Table 5. Overview of cost items incurred. If costs are reported per trip, they are relative to the transport from Switzerland to Iceland only; in case of "per roundtrip" cost, this also includes the return trip to Switzerland which was prepaid but not completed in 2024.

		Unitary costs	Total costs (CHF)
CO_2 supply	CHF/tCO_2	125	35'400
Isotainer rental	CHF/month/isotainer	2'520	252'000
Chassis rental	CHF/month/chassis	900	20'700
Truck transport	CHF/trip/isotainer	1'200	35'000
Train transport	CHF/roundtrip/isotainer	1'700	25'000
Ship transport	CHF/trip/isotainer	1'650	46'000
Total	-	-	414'100

4.3 Life-cycle assessment

4.3.1 Life-cycle inventory analysis

In the following, we provide an overview of the life-cycle inventories used in the environmental assessment of the CCTS supply chain for the conditioning of CO_2 captured at Ara Bern in Switzerland, multimodal transport to Iceland, and injection at the dedicated injection well by Carbfix in Helguvík.

CO_2 conditioning

The LCA considers a conditioning plant model of a comparable liquefaction process based on R449A from the literature [21] line with WP2. To ensure the accuracy of the literature model, we compared the electricity consumption measured during the demonstration from September 2023 to September 2024 to the consumption reported in literature [21] and found excellent agreement with a deviation by less than 1 %. We assume the consumer electricity grid mix of the FOEN [22] with a higher climate change impact compared to the ecoinvent grid mix. The main assumptions are summarized in Table 6.

Table 6: Main assumption of the CO_2 conditioning model based on [21].

	value	unit	comment
electricity demand	240.3	kWh/t CO_2	*consumer electricity grid mix of the Federal Office for the Environment (Luana and Frischknecht, 2021) is assumed; demand is based on average electricity consumption of the conditioning unit from September 2023-September 2024*
refrigerant R449A	55	kg	
leakage rate refrigerant	5.5	kg/a	R449a, represented by R134a with similar climate change impact

annual capacity	2128.7	t CO_2/a	
steel	10	t	Including metal working
plant lifetime	20	a	
annual full load hours	7884	h/a	

CO_2 transport

The CO_2 transport step considers the production of the iso-container, and the transport modes required to move the iso-container with CO_2 from the source to the injection site and the return trip. In the assessment, the cryogenic iso-container for CO_2 transport is modeled based on a representative cryogenic iso-container for CO_2 transport (ASCO 20‘ ISO tank container, ASCO CARBON DIOXIDE LTD). The inventory for the iso-container is reported in Appendix 11.1.

We report upper bounds of CO_2 losses in the demonstrator transport chain based on the mass difference of CO_2 processed at Ara Bern in Switzerland and unloaded at Carbfix in Iceland. The mass differences can be attributed partly to the accuracy of measurements and partly to the pioneering nature of the demonstration that requires experimentation and testing. With increasing operational experience and supply chain optimization, we expect the mass differences to fall. Further, the holding times of the iso-containers used for the demonstration range between 64 to 187 days based on supplier data and are thus well above the duration of the trips**Fehler! Verweisquelle konnte nicht gefunden werden.**. Therefore, we separately report the upper bounds of CO_2 losses during transport in the LCA.

The *climate change impact* of CO_2 transportation in initial assessments is dominated by freight train transport in Germany and freight ship transport between Rotterdam and Reykjavik, the segments of the trips with the longest travel distances (Table 7). Hence, we improve the representation of the two transport segments with tailored models.

We adapt the electricity mix of the ecoinvent model for freight transport via train based on the annual electricity mix for rail customers as provided to us by the municipal utility company *Stadtwerke Tübingen GmbH*, which supplies the electricity for the CO_2 transport via train in Germany within DemoUpCARMA. The inventory for the modeled electricity mix is reported in Appendix 11.1.

In addition, we identified two typical ships of the logistics company *Samskip* traveling between Rotterdam and Reykjavík based on the *Port of Rotterdam's* arrival and departure schedule[6]. Based on the identified ships with a deadweight tonnage of 5500-5600 t, we model ship transport of CO_2 between Rotterdam and Reykjavík using the ecoinvent model for sea transport via similar-sized cargo ferries. We adjust the ecoinvent model of transport via cargo ferry by adapting the fuel consumption to the average value for cargo ships in the Netherlands with a deadweight tonnage of 5000-9999 t. The emissions from fuel combustion are adjusted accordingly using representative emission factors for CO_2, CH_4, CO, N_2O, NO_x, NMVOC, SO_x, PM_{10}, and $PM_{2.5}$ [23].

The environmental impacts of the remaining transport modes required to move CO_2 from source to sink are based on processes of ecoinvent 3.8 (cut-off) [15] and estimated using Carculator [24] (Table 7).

Table 7: Sources of life-cycle inventory of CO_2-transport modes

transport	one-way	source	comment

[6] https://www.portofrotterdam.com/en/up-to-date-information/arrival-and-departures; identified ships Samskip Skaftafell and Samskip Hoffell, accessed November 04, 2024.

mode	distance in km		
freight train, Germany	648	[15]	based on electric freight train, with the electricity source adjusted to the electricity mix of rail customers as reported by the utility company supplying the German train transport in DemoUpCARMA (Stadtwerke Tübingen GmbH)
freight train, Netherlands	130	[15]	based on electric freight train, electricity source adjusted to Dutch electricity mix from ecoinvent
cargo ship	2150	[15, 23]	based on cargo ferry, with fuel consumption and combustion emissions adjusted based on average value for cargo ships in the Netherlands
lorry, Switzerland	107	[24]	compressed biogas from sewage sludge, 44t gross weight, 2020, EURO-VI available payload: 28716 kg, payload 19562 kg,, curb mass 15208 kg
lorry, Iceland	57	[24]	diesel, 44t gross weight, 2020, EURO-VI available payload 29069 kg, payload 19562 kg, curb mass 14855 kg

CO_2 storage

Assessments of permanent geological storage facilities for CO_2 are limited to a few studies [25-27]. Therefore, DemoUpCARMA assesses the environmental impact of the injection site using primary data supplied by Carbfix based on the construction and operation of the dedicated injection site in Helguvík.

The first assessment of a dedicated geological storage facility based on demonstrator data increases confidence in the LCA results and provides a reference in the literature. The demonstrator data covers the construction work at the injection site, including drilling of the wells, and the equipment, including seawater and injection pumps, control and monitoring facilities, piping, cables, and casings. Further, we consider the electricity consumption for evaporation, pumping, and injection during the demonstration. Carbfix also provides an estimate of the capacity of the demonstrator injection well.

The inventory derived from the demonstrator data reflects the pioneering nature of the injection site. For instance, CO_2 was injected in only 83 of the 227 days reported of operation. This, coupled with lower injection rates during the initial start-up tests and experiments, resulted in a high electricity consumption per tonne of CO_2 injected over the project duration (390 kWh/t CO_2). In the later months of the project (e.g. May, June, and August 2024), injection rates were higher and more representative of regular commercial operations, resulting in much lower electricity consumption per tonne of CO_2 injected. For example, in the 11 days of continuous CO_2 injection in mid-August, electricity consumption was only 156 kWh/t CO_2. It is worth noting that even 11 days is a short period of continuous injection. Therefore, further reductions in electricity consumption are expected across longer periods of continuous injection.

The injection capacity is based on preliminary annual injection rates, which are conservatively estimated by Carbfix for the demonstrator well and will likely be higher for commercial injection sites.

The inventory for the injection facilities is reported in Appendix 11.1.

4.3.2 Life-cycle impact assessment

The environmental assessment shows that the demonstrator chain effectively reduces GHG emissions over the full life-cycle. For every ton of CO_2 captured, the CCTS chain causes 0.26 t of CO_2-eq GHG emissions, effectively reducing 0.74 t of CO_2-eq GHG emissions, see Figure 15. Life-cycle GHG emissions of the CCTS chain are dominated by transport due to the long distance from land-locked Switzerland to Iceland. Over three-quarters of GHG emissions of the CCTS chain result from the transport step, with ship transport from Rotterdam to Reykjavik and rail transport in Germany alone accounting for 64 % of total GHG emissions of the CCTS chain.

The contributions of the conditioning and of the permanent storage steps are small in comparison to the transport step due to low-GHG-intensity electricity supply both in Switzerland and Iceland. In particular, the permanent storage step contributes only 0.02 t of CO_2-eq GHG emissions for every ton of CO_2 captured, despite assuming the high electricity consumption over the project duration. When assuming a reduced electricity consumption based on the measurements during continuous injection, the climate change impact of permanent storage is almost halved. Note that the assessment excludes the biogas upgrading, where CO_2 is captured, as the biogas upgrading is allocated to the production of biomethane, where CO_2 is produced as a waste product.

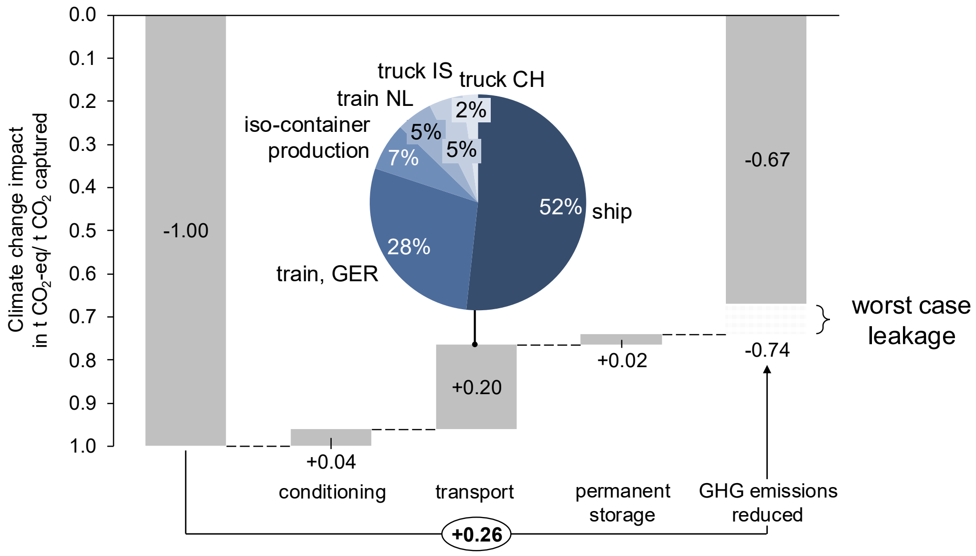

Figure 15: Climate change impact per ton of CO_2 captured, transported and stored over the full life-cycle of the supply chain. Values are given in tons of CO_2-equivalent greenhouse gas emissions (GWP100). The carbon capture, transport, and storage chain emits 0.26 t of CO_2-equivalent GHG emissions per ton of CO_2 captured and processed over the full life-cycle, effectively reducing 0.74 t of CO_2 emissions. The effectiveness of the supply chain is reduced by an additional 0.07 t of CO_2, when assuming all mass discrepancies between loading and unloading of CO_2 to be due to leakage in the worst case (hatched area).

The effectiveness of the CCTS chain is reduced by an additional 0.10 t of CO_2-eq GHG emissions when assuming all mass discrepancies between loading of CO_2 at Ara Bern and unloading of CO_2 at Helguvík to be due to CO_2 leakage in the transport chain. The worst-case assumption reduces the GHG emission reductions to 0.63 t of CO_2-eq for every ton of CO_2 captured.

The dominance of transportation in the climate change impact of the CCTS chain is due to the current GHG-intensive fuel supply for transport, in particular the emission intensity of the electricity supply for freight train transport in Germany and the fossil-fuelled cargo ship transport. A reduction of transportation impact via defossilization of energy supply, alternative transport methods, or a reduction of transport distance may substantially improve the effectiveness of CCTS chains for Switzerland.

In addition to life-cycle GHG emissions resulting from transport, the worst-case leakage during transport would constitute a substantial penalty on the effectiveness of the CCTS chain if confirmed. The worst-case leakage assumes all measured mass discrepancies between loading and unloading of CO_2 to be due to leakage. However, the discrepancies can be attributed partly to the accuracy of measurements and partly to the pioneering nature of the demonstration that requires experimentation and testing.The worst-case leakage thus likely overestimates CO_2 leakage in commercial CO_2 transport.

Environmental impacts of the CCTS chain in impact categories other than climate change are also dominated by the transport step (Figure 16), with the share exceeding 60 % in 12 out of 16 impact categories. The impact category *ionizing radiation* is dominated by the conditioning step due to electricity consumption from thermal nuclear power plants during the conditioning of CO_2. The geological storage step is the largest contributor to *water use*. The impact is due to the hydroelectric power consumption in Iceland, which assumes water evaporation from reservoirs. In particular, the impact is not due to water use for the injection of CO_2 into the reservoir.

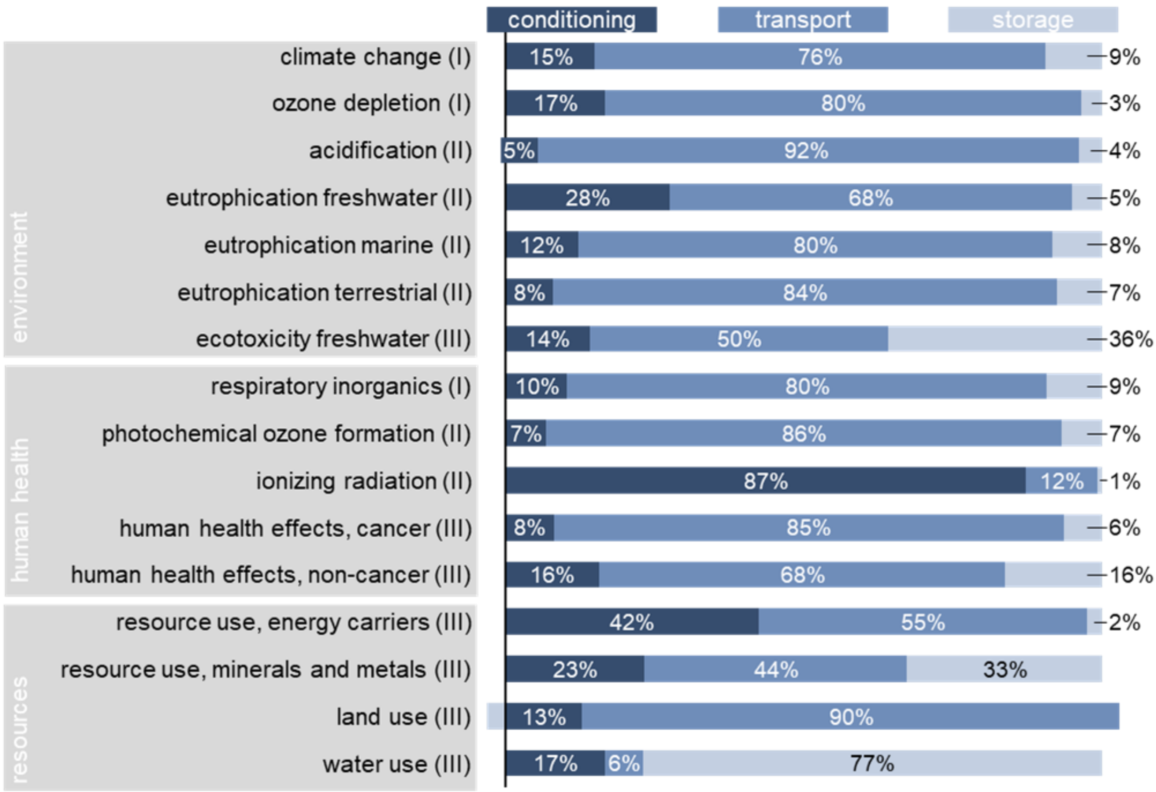

Figure 16: Relative contribution to environmental impacts of the conditioning, transport, and storage steps of the carbon capture, transport, and storage chain. Absolute values are provided in Appendix 11.2.

4.4 Key regulatory gaps

Using the procedures and methodologies as described in Section 3.5, we identified key regulatory gaps, learnings and further considerations for each project in WP2 and WP3.

4.4.1 Key regulatory gaps for demonstration of CO2 utilization and storage in concrete (WP2)

Swiss concrete standard SN EN 206-1

In collaboration with Kästli Bau AG and Neustark, EMPA investigated the development of low-carbon concrete mixtures based on the Neustark technology. This technology produces carbonated recycled concrete aggregates (RCA), which can be used to produce recycled concrete, while the application of this aggregate increases the compressive strength of the concrete produced. As a result, the minimum cement content required for the compressive strength of the concrete can be reduced without compromising these strength requirements. However, such a reduction is not given in the present day-to-day operations due to the minimum cement content currently required and specified for primary and recycled concrete in the Swiss concrete standard SN EN 206-1[7][8]. In accordance with European concrete regulations, this standard specifies requirements for concrete based on properties such as compressive strength and durability. It also defines limit values for certain components used in the production process, including the mentioned minimum cement content.

This SN EN 206-1 standard did not have a direct impact on the technology used by Neustark in the pilot project, as the standard does not limit the proportion of RCA or the amount of CO_2 that can be permanently stored. However, it challenges future research on reducing construction emissions, as the minimum cement content limits the potential to lower concrete's carbon footprint, given cement's high CO_2 intensity in concrete production.

As initial tests showed that the required concrete properties can also be met with a lower cement content and due to the enormous pressure to reduce emissions in this industry, an adaptation of the standard was to be expected. This amendment to SN EN 206-1, which particularly affects Annex ND of the standard, will be published and enter into force at the beginning of 2025. Consequently, the minimum cement content will no longer have to be met by concrete manufacturers to produce recycled concrete according to Annex ND. This flexibility offers more opportunities to decarbonize concrete production without the constraint of a high carbon footprint of the cement.

In addition, with the amendment of the Swiss concrete standard SN EN 206-1 Annex ND, two new standards SIA 215/1 and SIA 215/2 will also be introduced, with the former focusing on requirements for new cements and the latter on the requirements for new additives for concrete [28]. These standards should ensure the quality, safety and suitability of these materials for use in construction and therefore guarantee the durability and performance of concrete structures, including those using the novel concrete type in accordance with Annex ND.

This amendment to the standard will also entail changes for the stakeholders in the value chain, including concrete manufacturers [29]. Concrete manufacturers must ensure that the various concrete mixtures, such as normal, high-strength, lightweight or recycled concrete, meet certain performance

[7] In addition to SN EN 206-1, other standards are relevant for producing recycled and primary concrete. For recycled concrete, these include SN 670115 (Petrography of aggregates), FOEN guidelines (Utilisation of mineral construction waste), SIA 162/4 (Recycled concrete), and further SN standards [30]. For primary concrete, SIA 262 (Concrete construction) applies, based on SIA 262/1 (Supplementary requirements) and, like recycled concrete, based on SN EN 206-1 [31].

[8] Bundesamt für Strassen (2007, December). Betoneigenschaften nach SN EN 206-1. Retrieved from https://www.tfb.ch/Htdocs/Files/v/5899.pdf/Publikationsliste/08BetoneigenschaftennachSNEN2061BerichtVSSNr615.pdf.

and quality criteria, including the already mentioned compressive strength, durability and resistance to environmental influences. To prove compliance with these standards, concrete manufacturers must use various test methods. Due to their composition, many concrete mixes have similar performance characteristics, so they can be grouped together for testing and production. The production of the new recycled concrete type with a lower cement content in accordance with Annex ND requires further testing to ensure its quality. Standard composition regulations, like minimum cement content and w/c value[9], no longer apply, making it incompatible with traditional concrete testing methods. This increases the difficulty and resource-intensiveness of testing procedures, which in turn drives up costs. As a result, larger rather than smaller concrete manufacturers are more likely to test and produce this new type of recycled concrete, as the adaptation to these tightened testing requirements and providing the needed resources are more feasible for them than for smaller firms [29].

Further considerations

Comparability and economic sustainability

Another key consideration of relevant project partners concerns the need for regulations that enhance the comparability of concrete products with varying levels of sustainability (AG, 2024). While existing standards provide a basic framework, they lack the precision that stakeholders, including potential customers, policymakers, and regulators, need to fully comprehend and differentiate the environmental and performance benefits of decarbonized concrete and therefore to assess products not only based on their carbon footprint but also according to resource efficiency, availability or product quality.

Better comparability would allow stakeholders to make more informed decisions and recognize the tangible benefits of sustainable options. This in turn could encourage a willingness to pay a premium for products with improved environmental performance, especially if the broader benefits are widely understood and appreciated.

However, economic viability remains a significant hurdle, as the current cost of biogenic CO_2 is high at CHF 200 to 250 per ton. To ensure broad acceptance, these costs must be significantly reduced over time. While subsidies and incentives can play a crucial role in the initial phase of market development, the overall aim is to establish a self-sustaining market where such solutions can thrive independently of financial support.

4.4.2 Key regulatory gaps for demonstration of CO_2 transport and geological storage (WP3)

Declaration of CO_2

Based on workshops conducted with the relevant project partners Carbfix, Neustark, Salzmann Transporte and SBB Cargo in October 2022, the declaration of CO_2 was identified as a key regulatory gap. In this project, the declaration of CO_2 refers to whether it could have been classified as a 'chemical good' or as 'waste' when being transported across international borders.Iceland, as a member of the European Free Trade Association (EFTA) and a signatory to the Basel Convention, has implemented the CCS Directive to create a legal framework for the geological storage of CO_2. In

[9] W/c ratio: Mass ratio of water to cement; in accordance with SN EN 206-1, the w/c ratio is determined from the batch record (Bundesamt für Strassen , 2007).

principle, CO_2 captured and transported for the purpose of geological storage within the scope of the CCS Directive is excluded from the Waste Framework Directive and is therefore not treated as 'waste'[10]. However, the CCS Directive applies only to commercial CCS projects with a total intended storage of at least 100'000 tons of CO_2, effectively exempting smaller-scale projects from certain approval or authorisation requirements [32]. Consequently, the project partners assumed that the CO_2 transported and geologically stored abroad within the DemoUpCARMA pilot and demonstration project would not be treated as 'waste' but as a 'chemical good'. This assumption was aligned with Swiss operations of Neustark. Nevertheless, discrepancies in regulatory interpretation across jurisdictions required adjustments in transport procedures, as mentioned in the part about CO_2 cross-border shipments in Subsection 4.1.

To facilitate international CO_2 shipments, Neustark applied for the Unilateral export permit at FOEN, which is valid for 12 months. For this permit to be issued, several requirements had to be met:

- Prove that Carbfix can durably store the CO_2 received from the pilot
- Guarantee that the CO_2 will be stored within a certain number of days after crossing the Swiss border
- Definition of the steps of the processes in the pioneering chain from capture to storage as well as definition of all involved parties
- Security deposit in case the CO_2 is not injected and therefore durably stored
- Consignment certificates for each transport

Within Iceland, the classification of CO_2 as a 'chemical good' for transport required Carbfix to complete specific forms, adding procedural steps but not significantly hindering logistics. Greater coordination required alignment with international regulations. For instance, understanding the requirements of other countries' authorities and adapting to the train operator's conditions for transporting isotainers classified as 'waste' involved additional efforts to ensure compliance and smooth logistics.

With these new requirements for CO_2 classification, the pioneering project faced additional lead times and reduced flexibility due to stricter procedures and definitions for involved parties, as well as higher costs from the added paperwork. Nevertheless, all parties viewed these measures as a temporary solution, with the longer-term objective of integrating international CO_2 transport and storage into the existing legal framework to simplify future operations. Following the issuance of the permit and the completion of forms, further isotainer shipments proceeded to Iceland, with Carbfix reporting no additional complications logistics [33].

It should be noted that Iceland has more than ten years of experience with underground CO_2 storage compared to other countries. As a result, its legal framework has already been further developed and established, simplifying such processes[11] In comparison, the cross-border transportation of captured and liquefied CO_2 was a first attempt for Switzerland, meaning that the regulatory context for such a project must first be established. The difficulty therefore lies in the existing or yet-to-be-developed regulations between the countries and environmental authorities involved, which is why international cooperation requires more advanced planning and more short-term adaptation.

Further considerations

[10] European Commission. (2023, 10 24). REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52023DC0657.

[11] Ministry for the Environment, Energy and Climate and the Environment Agency in Iceland. (2023). Report on Implementation of Directive 2009/31/EC on the geological storage of carbon dioxide, Iceland. Retrieved October 25, 2024, from https://ec.europa.eu/assets/clima/ccs/2023/policy_ccs_country_report_2023_iceland_en.pdf.

Administration and organisation of materials

Another consideration emerged around the administration and logistics of research materials between Iceland and Switzerland. Specifically, the issue involved the ETH research equipment utilized by Carbfix in Iceland. Since Carbfix operates as a private company, Icelandic Value Added Tax (VAT) regulations [34] entitled Iceland to charge VAT on this equipment after it resided at their locations for a certain period. However, as DemoUpCARMA was declared a research project and research equipment is generally exempt from VAT, this tax claim posed an unforeseen obstacle for the Carbfix project leaders on-site and caused delays in the project's progression (Carbfix, 2024).

Consequently, this example demonstrated the challenges faced when conducting a research project with a private company like Carbfix, as such projects may not receive the same recognition and favorable conditions as those conducted with official research institutions, such as local universities.

4.4.3 Summary

As WP2 and WP3 were both pilot and demonstration programs, they were subject to a less stringent regulatory framework compared to commercial projects [35-38]. This more flexible setup allowed for a primary focus on proving the technical feasibility of these projects and exploring innovative approaches without the immediate constraints of commercial regulations. However, while this flexibility enables technical exploration, it also creates potential for unforeseen regulatory gaps when moving from pilot to commercial scale, as stricter guidelines are required for broader application.

In WP2, the demonstration of CO_2 utilization and storage in concrete using Neustark's technology encountered generally fewer regulatory hurdles due to the established standards and guidelines for concrete production in Switzerland. These standards, including the Swiss Concrete Standard SN EN 206-1, initially posed limitations due to their prescriptive nature, particularly around minimum cement content, which constrained emission-reducing innovations. Similar regulatory challenges were observed in other international projects, such as CarbonCure in Canada and the United States, where outdated prescriptive standards restricted the adoption of CO_2-mineralized concrete. CarbonCure responded by advocating for a shift to performance-based standards, allowing for innovation while ensuring compliance with strength and durability requirements [39]. Switzerland's upcoming 2025 amendment of SN EN 206-1 and related standards, such as SIA 215/1 and SIA 215/2, reflects a similar approach, releasing restrictive specifications and allowing for greater flexibility in adopting low-carbon concrete technologies. However, further adoption depends on the support of key stakeholders, particularly building owners, who can drive demand for low-carbon concrete in construction projects.

WP3, on the other hand, introduced an entirely new set of challenges, as it involved processes that are unprecedented within the industry. Unlike WP2, which fits into an industry with established practices and standards, WP3 encompasses novel activities such as capturing, transporting, and durably storing CO_2 underground. The cross-border nature of this project added a further layer of complexity, particularly in terms of regulatory compliance between Switzerland and Iceland. The classification of CO_2 as 'waste' led to procedural delays and additional compliance requirements, underscoring the need for a harmonized cross-border regulatory framework. Projects like Denmark's Project Greensand face similar complexities, indicating that international agreements could streamline regulatory pathways for CO_2 transport and storage [40]. For private companies like Carbfix, these challenges highlight the difficulty of integrating commercial entities into traditionally research-focused initiatives. In addition, DemoUpCARMA operated under a research injection permit, which exempted it from the requirement for an environmental impact assessment. For future commercialization of similar projects, such assessments will be mandatory for CO_2 injections exceeding 100,000 tons, as is already the case for other Carbfix projects, which could make implementation more difficult. These considerations point to the need for a proactive and multilateral legal framework for such projects that not only addresses scientific and technical, but also administrative challenges.

The successful implementation of these pilot projects provides valuable insights for policy makers, particularly in designing regulatory frameworks that support the transition from research to market readiness. These efforts could promote comparability in the marketplace so that low-carbon technologies can compete fairly and sustainably, or by creating multilateral agreements early on, so that cross-country and cross-institutional regulations can be applied. In addition, public acceptance remains a critical factor for future projects, especially those with underground storage, where providing transparency and education on risks and safety measures can favorably influence local support.

5 Conclusions

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

- The CO_2 transport solution is technically feasible, although unforeseen regulatory requirements have caused an additional administrative burden (i.e., application for unilateral waste handling permit). Furthermore, this highlights that there is the need to harmonize 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). In this context, the FOEN is working on initiatives to update CO_2 storage regulations, aiming to align with both national and international climate goals. These efforts focus on establishing clear guidelines for CO_2 storage projects, including biological and geological methods, to support Switzerland’s path toward climate neutrality by 2050.
- The CCTS chain is expected to enable GHG emission reduction, as GHG emissions resulting from the life-cycle of conditioning, transport, and geological storage are far lower than the amount of GHG emissions reduced via geological storage, provided the capture of CO_2 is associated with low GHG emissions as well.
  Furthermore, the CCTS supply chain can contribute to net-negative emissions if the share of CO_2 captured with biogenic origin is sufficiently high. For the wastewater treatment plant Ara Bern, all of the CO_2 captured from the biogas upgrader is certified to be of biogenic origin.
- Fossil-based international transport is responsible for an overwhelming share of the environmental impacts of CCTS. Hence, planning international CO_2 transport infrastructure requires particular attention. We expect the introduction of large-scale transport infrastructure to lower the environmental impact of future CCTS chains, accelerated by the continuing defossilization of the European electricity grid and stricter environmental regulation of shipping and freight transport.
- The global economic and geopolitical situation has made material procurement challenging during the first year of the DemoUpCARMA project.

6 Outlook and next steps

DemoUpCARMA WP3 has sparked further innovative projects in the CCS field: (1) the CITru project, which focuses on exploring the potential for permanent underground CO_2 storage; and (2) the Werdhölzli CCS project in Zurich, which aims to capture CO_2 from the city's sewage sludge incineration plant. The project plans to capture up to 20,000 tons of CO_2 per year, with half of the captured CO_2 to be stored in recycling concrete in Switzerland, while the other half will be transported and stored safely beneath the North Sea. This project, along with its budget, was approved by Zurich's citizens on September 22, 2024. Going forward from DemoUpCARMA, an upscaling of CCTS activities in Switzerland requires the establishment of large-scale shared CO_2 transport infrastructure, such as pipeline transport, to lower both cost and environmental impacts [8, 41]. The upscaling of these solutions has been addressed in WP4 of DemoUpCARMA; results and insights are presented in the corresponding report.

7 National and international cooperation

DemoUpCARMA and particularly this work package relies 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 SFOE and FOEN, to discuss the WP progress and to visit the injection sites at Helguvík and Hellisheiði.

8 Communication

The project communication is part of Work Package 1.

9 Publications

Not applicable.

10 References

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11 Appendix

11.1 Life-cycle inventories

Iso containers

The isocontainers are modeled based on the weight of two representative iso-containers of the producers HOYER and KARBONSAN, which have an approximate weight of 8 t, and a volume of 20.0-20.9 m^3. Based on the density of liquid CO_2 at -35 °C and 15-18 bar, and on the density of gaseous CO_2 at 15-18 bar, we assume the CO_2 effectively transported to be 21.6 t. Based on the roundtrip duration, we assume up to 10 shipments per year and a lifetime of 20 years for the isocontainers.

Table 8: Inventory for the construction of the iso-containers for CO_2 transport.

process	location	value	unit
market for steel, chromium steel 18/8	GLO	8000	kg
market for metal working, average for chromium steel product manufacturing	RER	8000	kg

Electricity mix train transport Germany

CO_2 transport via freight trains in Germany is modeled using the ecoinvent process for electric freight train transport, with the electricity mix adjusted to represent the German grid mix better. The electricity mix assumed for freight train transport in Germany is based on the electricity mix reported by the municipal utility company supplying the freight train operator. The climate change impact of the modeled electricity mix is 0.533 kg/kWh.

Table 9: Inventory for heat and electricity production.

process	location	value	unit
electricity production, hard coal	DE	0.101157	kWh
heat and power co-generation, hard coal	DE	0.016467	kWh
electricity production, lignite	DE	0.224386	kWh
heat and power co-generation, lignite	DE	0.00599	kWh
electricity production, oil	DE	0.01137	kWh
heat and power co-generation, oil	DE	0.00363	kWh
electricity production, natural gas, combined cycle power plant	DE	0.022852	kWh
electricity production, natural gas, conventional power plant	DE	0.014152	kWh
heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical	DE	0.001276	kWh
heat and power co-generation, natural gas, conventional power plant, 100MW electrical	DE	0.07772	kWh
electricity production, nuclear, boiling water reactor	DE	0.003834	kWh
electricity production, nuclear, pressure water reactor	DE	0.014166	kWh
electricity production, wind, 1-3MW turbine, offshore	DE	0.047181	kWh
electricity production, wind, 1-3MW turbine, onshore	DE	0.184344	kWh

electricity production, wind, <1MW turbine, onshore	DE	0.033582	kWh
electricity production, wind, >3MW turbine, onshore	DE	0.020244	kWh
electricity production, hydro, reservoir, non-alpine region	DE	0.004821	kWh
electricity production, hydro, run-of-river	DE	0.025309	kWh
heat and power co-generation, biogas, gas engine	DE	0.063261	kWh
heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	DE	0.012591	kWh
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	DE	0.046027	kWh
electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	DE	0.036978	kWh
electricity production, photovoltaic, 570kWp open ground installation, multi-Si	DE	0.028711	kWh

Injection facilities

The injection facilities are modeled based on primary data from the construction and operation during the demonstration activities. The construction includes the drilling of the wells, and the equipment, including seawater and injection pumps, control and monitoring facilities, piping, cables, and casings. The electricity consumption for evaporation, pumping, and injection reflects average values during the demonstration at Helguvík.

Table 10: Inventory for the construction of the dedicated injection facility, including the injection and monitoring wells, equipment for injection, and piping. We assume an injection capacity of 30 kt over the lifetime if the injection facility.

process	location	value	unit
Groundwork			
market for sand	CH	130000	kg
market for gravel, crushed	CH	1304000	kg
Transport lorry in market for gravel, crushed	CH	61440000	kg km
excavation, hydraulic digger	RER	4729.01	m3
Transformation, from unspecified, natural (non-use)		256	m2
Transformation, to industrial area		256	m2
Occupation, industrial area	IS	5120	m2a
Drilling			
market for diesel, burned in building machine	GLO	1,007,914	MJ
market for electricity, medium voltage	IS	50,576	kWh
market for concrete, normal	CH	31	m3
freshwater		4059000	kg
Casing			
cement, all types to generic market for cement, unspecified	RER	2160	kg
market for steel, chromium steel 18/8	GLO	887.2	kg
market for metal working, average for chromium steel product manufacturing	RER	887.2	kg
market for polyethylene pipe, DN 200, SDR 41	RER	64.7340874	m
Ground pipes and cables			
market for polyethylene pipe, DN 200, SDR 41	RER	42.08	m

market for polyethylene pipe, DN 200, SDR 41	RER	132.02	m
Pumps			
market for cable, three-conductor cable	GLO	140	m
water pump, 22kW	GLO	0.25	unit
water pump, 22kW	GLO	0.1	unit

Table 11: Inventory for the operation of the dedicated injection facility per tonne of CO_2 stored during the demonstration period. Sea water demand based on [12]. The electricity consumption represents the average consumption during the total demonstration period, including system downtime, idling and experiment periods. Consumption is substantially lower per tonne of CO_2 injected during periods of continuous injection such as August 2024 when consumption was 156.02 kWh/t.

process	location	value	unit
market for electricity, low voltage	IS	389.56 (156.02)	kWh
Water, salt, ocean		35	t

11.2 Assessment results

Impact assessment based on the Environmental Footprint methodology for 1 t of captured CO_2 handled by the CCTS chain

Table 12. Life-cycle impact assessment results based on the Environmental Footprint 3.0 methodology for 1 t of captured CO_2 handled by the CCTS chain.

impact categories	Unit	conditioning	transport	storage	sum
climate change (I)	kg CO_2 eq.	3.91E-02	1.96E-01	2.44E-02	2.60E-01
ozone depletion (I)	kg CFC-11 eq.	5.52E-09	2.64E-08	1.11E-09	3.30E-08
acidification (II)	mol of H+ eq.	1.29E-04	2.49E-03	1.02E-04	2.72E-03
eutrophication freshwater (II)	kg P eq.	2.97E-05	7.30E-05	5.28E-06	1.08E-04
eutrophication marine (II)	kg N eq.	3.40E-05	2.22E-04	2.29E-05	2.79E-04
eutrophication terrestrial (II)	mol of N eq.	2.78E-04	2.90E-03	2.56E-04	3.43E-03
ecotoxicity freshwater (III)	CTUe	9.03E-01	3.18E+00	2.27E+00	6.35E+00
respiratory inorganics (I)	disease incidence	1.75E-09	1.35E-08	1.55E-09	1.68E-08
photochemical ozone formation (II)	kg NMVOC eq.	7.60E-05	9.64E-04	7.49E-05	1.11E-03
ionizing radiation (II)	kBq U235 eq.	8.78E-02	1.22E-02	6.58E-04	1.01E-01
human health effects, cancer (III)	CTUh	5.60E-11	5.80E-10	4.36E-11	6.80E-10
human health effects, non-cancer (III)	CTUh	7.25E-10	3.15E-09	7.50E-10	4.63E-09
resource use, energy carriers (III)	MJ	1.85E+00	2.40E+00	1.06E-01	4.35E+00
resource use, minerals and metals (III)	kg Sb eq.	8.14E-07	1.53E-06	1.13E-06	3.48E-06
land use (III)	soil quality index	1.98E-01	1.39E+00	-4.56E-02	1.54E+00

water use (III)	m3 world eq. deprived	7.69E-02	2.93E-02	3.53E-01	4.59E-01

Impact assessment based on the ecological scarcity 2013 method for 1 t of captured CO_2 handled by the CCTS chain

Here we report the life-cycle impact assessment results based on the ecological scarcity 2013 methodology developed by the Swiss Federal Office for Environment. The methodology introduces a subjective weighting of the different impacts, allowing for the aggregation of various impact categories. The results are reported here as an additional reference.

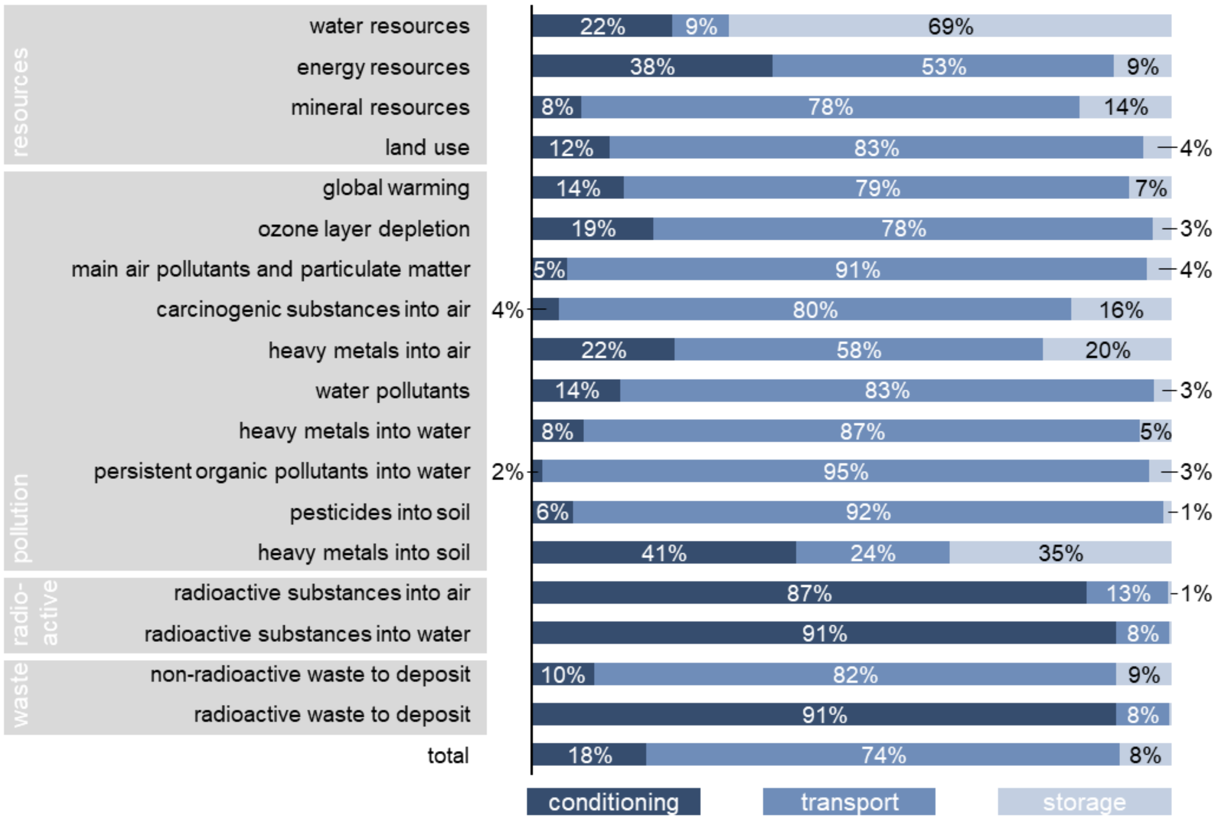

Figure 17. Relative contribution to environmental impacts of the conditioning, transport, and storage steps of the carbon capture, transport, and storage chain assessed via the ecological scarcity method.

Table 13. Life-cycle impact assessment results based on the ecological scarcity 2013 methodology for 1 t of captured CO_2 handled by the CCTS chain.

impact categories	conditioning	transport	storage	sum
water resources	1.09E+00	4.16E-01	5.01E+00	6.52E+00
energy resources	6.93E+00	9.35E+00	2.34E+00	1.86E+01
mineral resources	1.37E+00	1.29E+01	2.89E+0	1.71E+01

			0	
land use	3.26E-01	2.10E+00	1.40E-01	2.57E+00
global warming	1.75E+01	9.09E+01	1.08E+01	1.19E+02
ozone layer depletion	3.66E-02	1.44E-01	6.19E-03	1.87E-01
main air pollutants and particulate matter	6.89E+00	1.09E+02	5.89E+00	1.21E+02
carcinogenic substances into air	1.22E+00	2.20E+01	6.57E+00	2.98E+01
heavy metals into air	8.05E+00	1.97E+01	1.03E+01	3.81E+01
water pollutants	1.42E+00	8.12E+00	3.26E-01	9.86E+00
heavy metals into water	2.40E+00	2.43E+01	2.01E+00	2.87E+01
persistent organic pollutants into water	6.26E-02	3.41E+00	1.41E-01	3.62E+00
pesticides into soil	4.57E-03	6.29E-02	1.21E-03	6.87E-02
heavy metals into soil	1.25E+00	6.82E-01	1.52E+00	3.45E+00
radioactive substances into air	7.00E-06	9.71E-07	5.25E-08	8.02E-06
radioactive substances into water	3.22E-01	2.76E-02	1.90E-03	3.52E-01
non-radioactive waste to deposit	2.26E-01	1.79E+00	2.83E-01	2.29E+00
radioactive waste to deposit	2.90E+01	2.49E+00	1.72E-01	3.17E+01
total	7.81E+01	3.07E+02	4.84E+01	4.33E+02