DemoUpCARMA is funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN).

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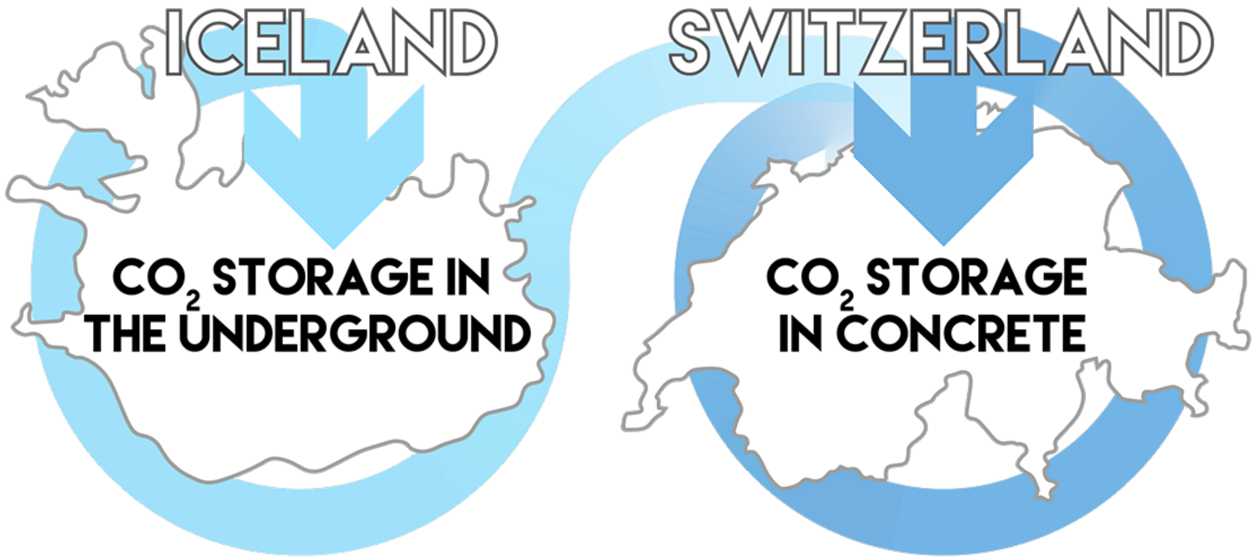
Demonstration and Upscaling of CARbon dioxide MAnagement solutions for a net-zero Switzerland



2021 – 2023+

ETH zürich, EPFL, PSI, Empa, eawag, Université de Genève, USI, RISIKO_DIALOG

Science, Research, NGO

JURA materials, arxada, Lonza, oraberh, scienceindustries Switzerland, Stadt Zürich Entsorgung + Recycling, VBSA ASED ASIR

Emitters

CASALE, ChemOil, SBB CFF FFS Cargo, KÄSTLI, SULZER, Salzmann AG Transporte, south pole, perspectives climate research

Solution providers

neustark, Carbfix, climeworks

Climate tech companies

Our programm today: part one

Welcome 13:00 - 13:20

Introducing DemoUpCARMA
Prof. Marco Mazzotti, ETH Zurich

DemoUpCARMA and Switzerland‘s climate strategy
Dr. Sophie Wenger, Federal Office for the Environment

Pilot and demonstration activities 13:20 - 13:50

Permanent CO_2 storage in recycling concrete
Dr. Johannes Tiefenthaler, Neustark AG

CO_2 cross-border transport and permanent storage in the underground
David Shu, ETH Zurich

Discussion and Q & A moderated by Dr. Viola Becattini

Zoom-in: science and technology 13:50 - 14:30

Carbonation of recycled concrete aggregates and its implications on recycling concrete
Dr. Andreas Leemann, Dr. Frank Winnefeld, Empa

CO_2 storage via in-situ mineralization
Salka Kolbeinsdóttir, Carbfix

Monitoring of CO_2 injection and storage in the underground
Prof. Stefan Wiemer, Swiss Seismological Service at ETH Zurich

Discussion and Q & A moderated by Prof. Marco Mazzotti

Coffee break 14:30 - 15:30

Our programm today: part two

Systemic aspects **15:30 - 16:30**

Life cycle assessment and system analysis of CO_2 capture, transport, and storage technologies
Prof. André Bardow, ETH Zurich

CO_2 capture integration in waste-to-energy plants: case study for the city of Zürich
Tuvshinjargal Otgonbayar, ETH Zurich

Perception of CO_2 management solutions in Switzerland
Dr. Irina Dallo, ETH Zurich, Dr. Samuel Eberenz, Stiftung Risiko Dialog

The role of carbon markets
Dr. Matthias Honegger, Perspectives Climate Group

CO_2 transport modes and infrastructure financing
Pauline Oeuvray, ETH Zurich

Discussion and Q & A moderated by Oliver Akeret

Panel discussion **16:30 - 17:15**

The future of CO_2 management
Dr. Viola Becattini (ETH Zurich), Dr. Sophie Wenger (FOEN), René Estermann (Environmental and health protection Zurich), Mario Davidi (Waste management and recycling, ERZ), moderated by Dr. Benedikt Knüsel (ETH Zurich)

Apéro (main hall) **17:15 - 18:30**

Pilot and demonstration activities

neustark®

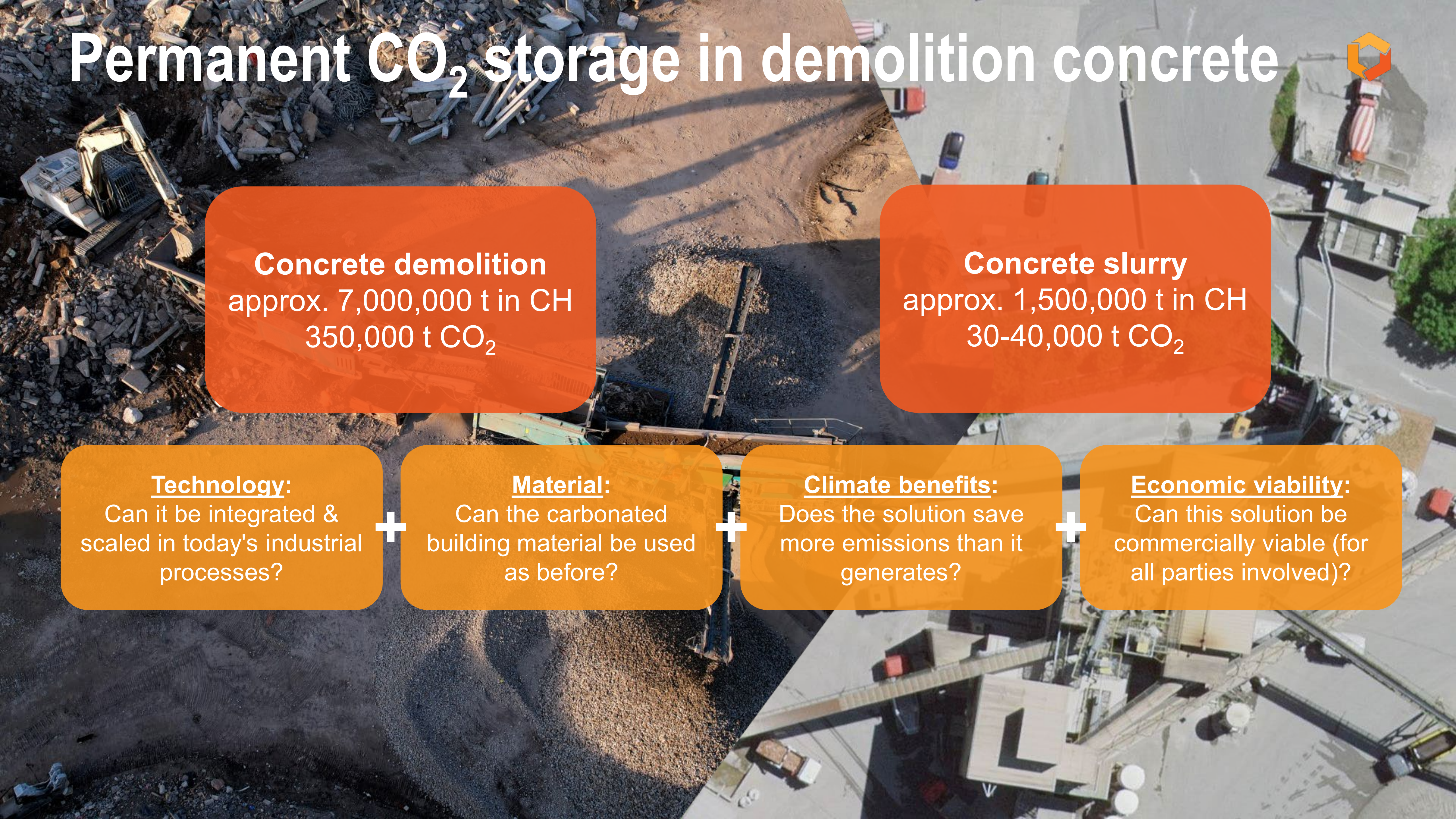
CO_2 storage in demolition concrete

DemoUpCARMA

6.12.2023

Johannes Tiefenthaler

Permanent CO_2 storage in demolition concrete



Concrete demolition
approx. 7,000,000 t in CH
350,000 t CO_2

Concrete slurry
approx. 1,500,000 t in CH
30-40,000 t CO_2

Technology: Can it be integrated & scaled in today's industrial processes?

+

Material: Can the carbonated building material be used as before?

+

Climate benefits: Does the solution save more emissions than it generates?

+

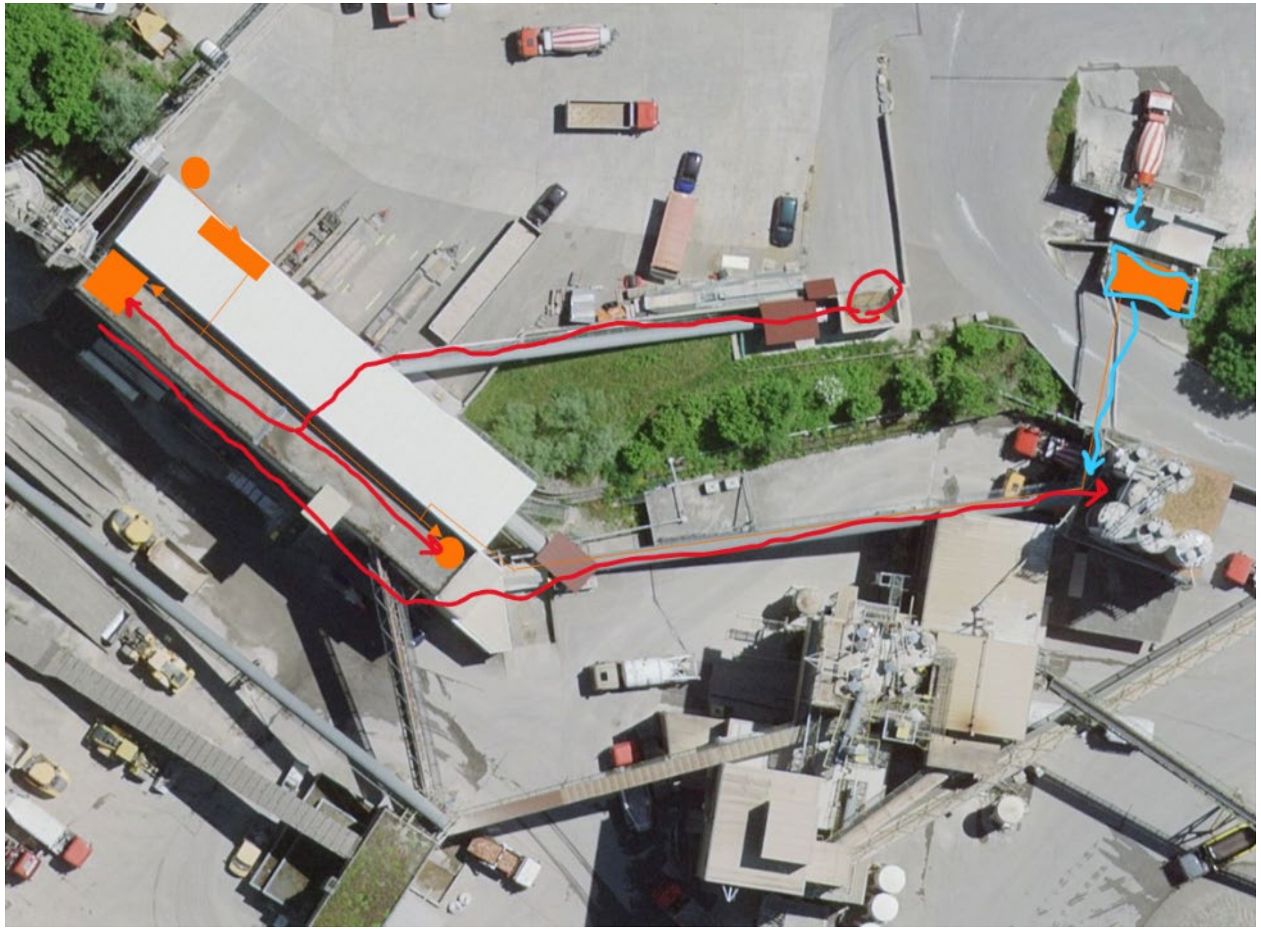
Economic viability: Can this solution be commercially viable (for all parties involved)?

Integrated storage sites sequester >100 t CO_2 !

Demolition concrete

- 13 kg CO_2 per t of concrete granulate
- 121 t CO_2 permanently stored during pilot project
- Potential 2023: 90,000 tons in CH
- Concrete deconstruction grows by a factor of 6 by 2050

CO_2-storage ecosystem at Kästli Bau, Berne



CO_2 -storage system Concrete granulate Concrete slurry

Concrete slurry

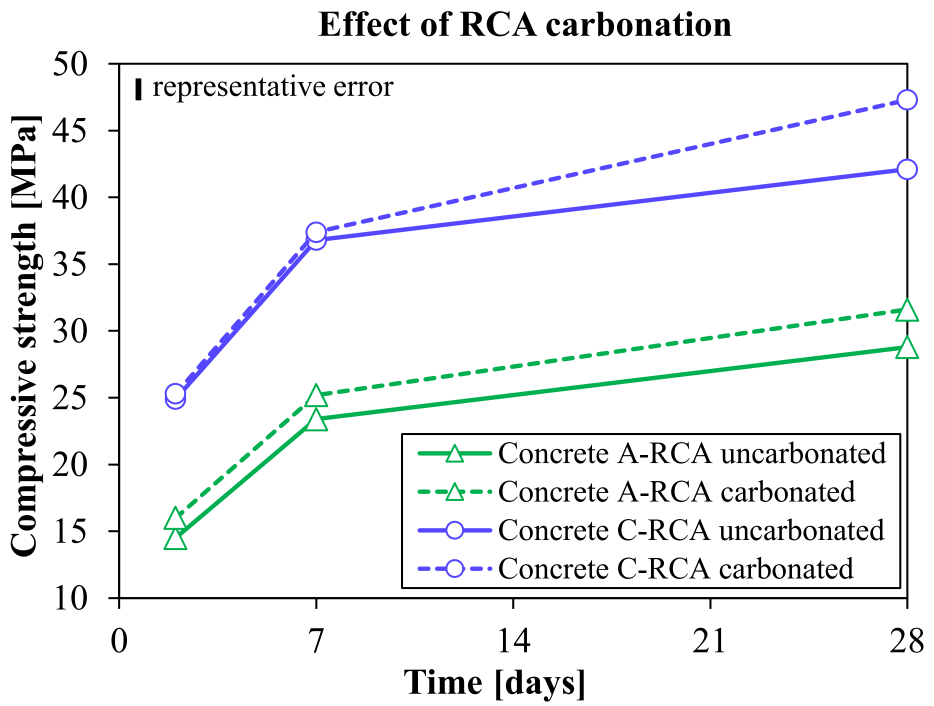
- 25 kg CO_2 per t sludge
- 12 t CO_2 stored in pilot operation
- Potential 2023: 30-40,000 t in CH

CO_2 sequestration has positive effects on the material properties of recycled concrete

<u>Concrete granulate:</u>
CO_2-enriched concrete granulate improves the compressive strength of fresh recycled concrete.

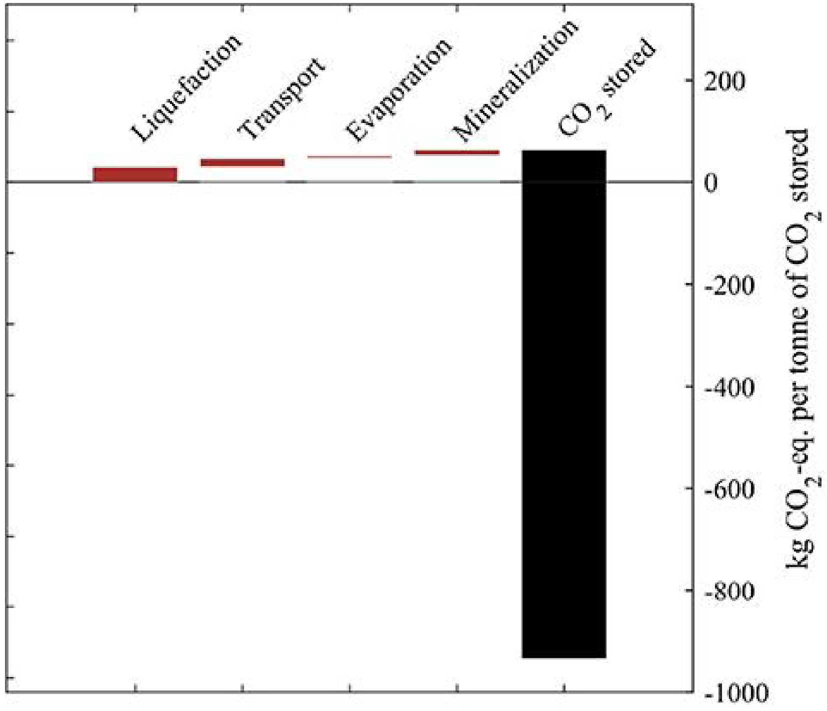
<u>Concrete slurry:</u>
The workability of primary concrete produced with concrete wastewater can be improved by carbonating it beforehand.

<u>In addition</u>:
Carbonated materials (concrete granulate, concrete slurry) can be used in the same way as today.



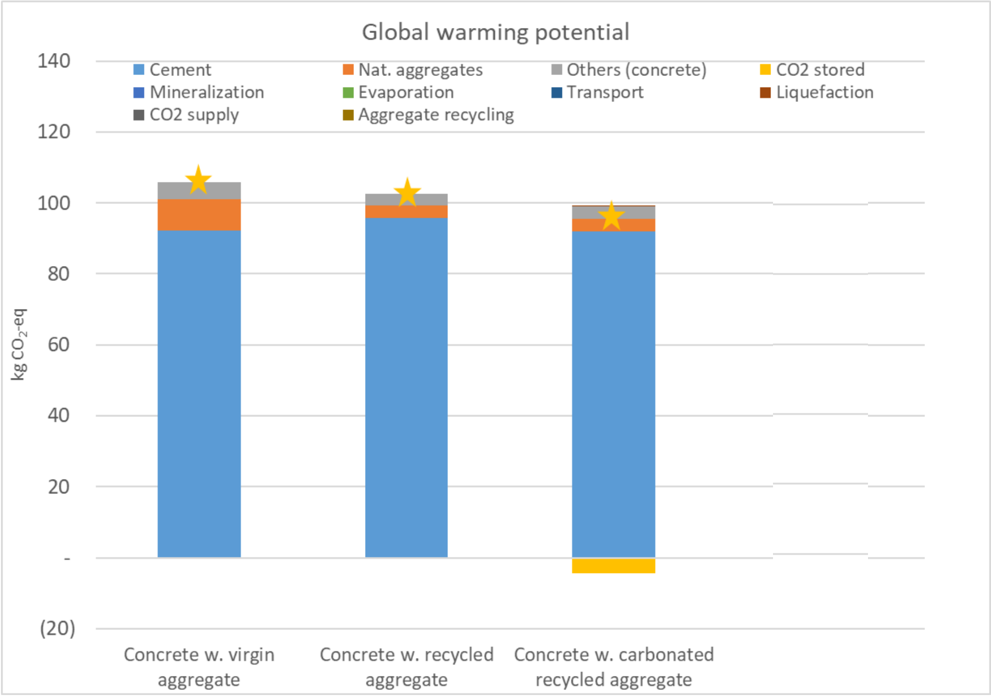
The value chain is >90% efficient

CO_2 storage



- >90% efficiency = 1 t CO_2 saved generates 950 kg net climate benefit
- 320 kWh/t CO_2 removed

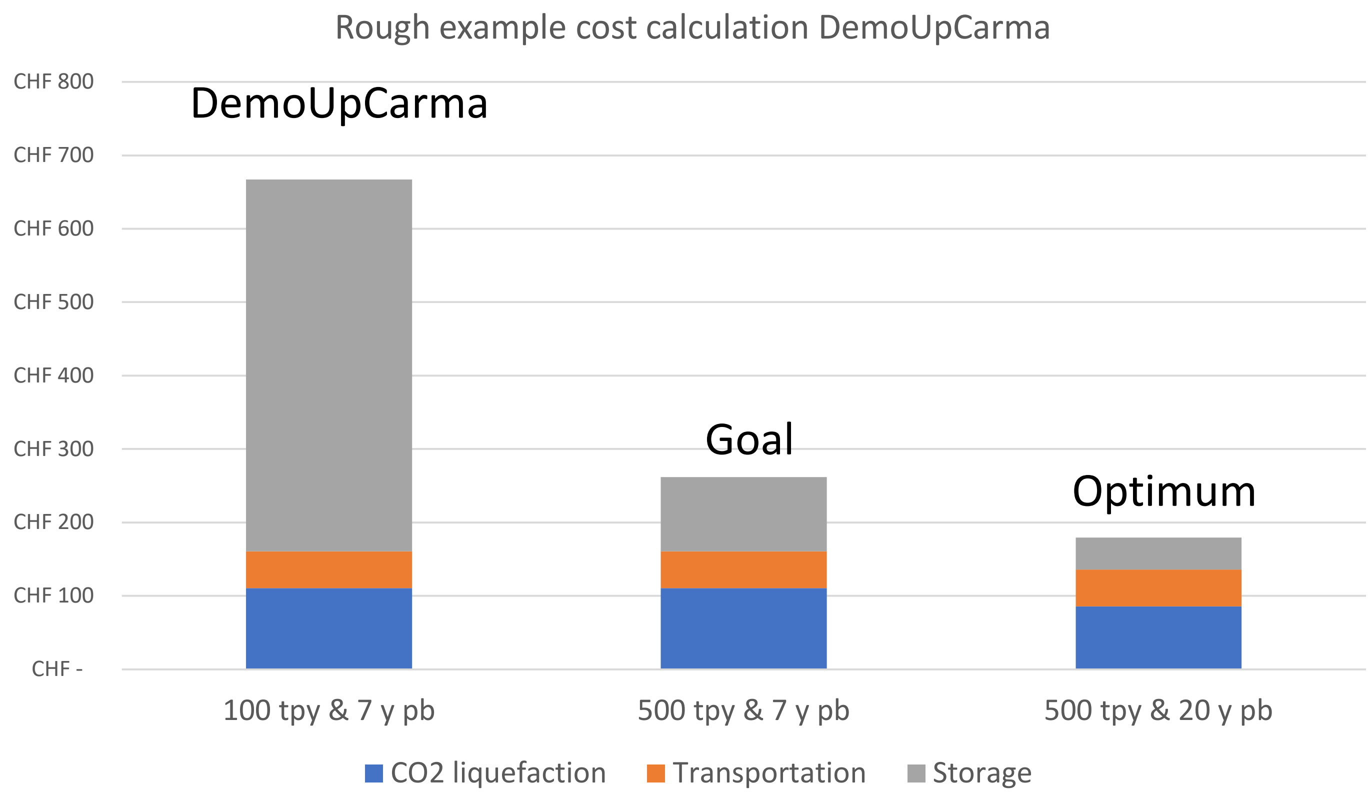
Material



CO_2 storage reduces energy consumption during the production process of recycled concrete

- 2.5 kg of cement saved: - 2 kWh of energy
- 4.5 kg CO_2 removed: + 1.5 kWh energy

High profit expectations on capital & low throughputs are cost drivers



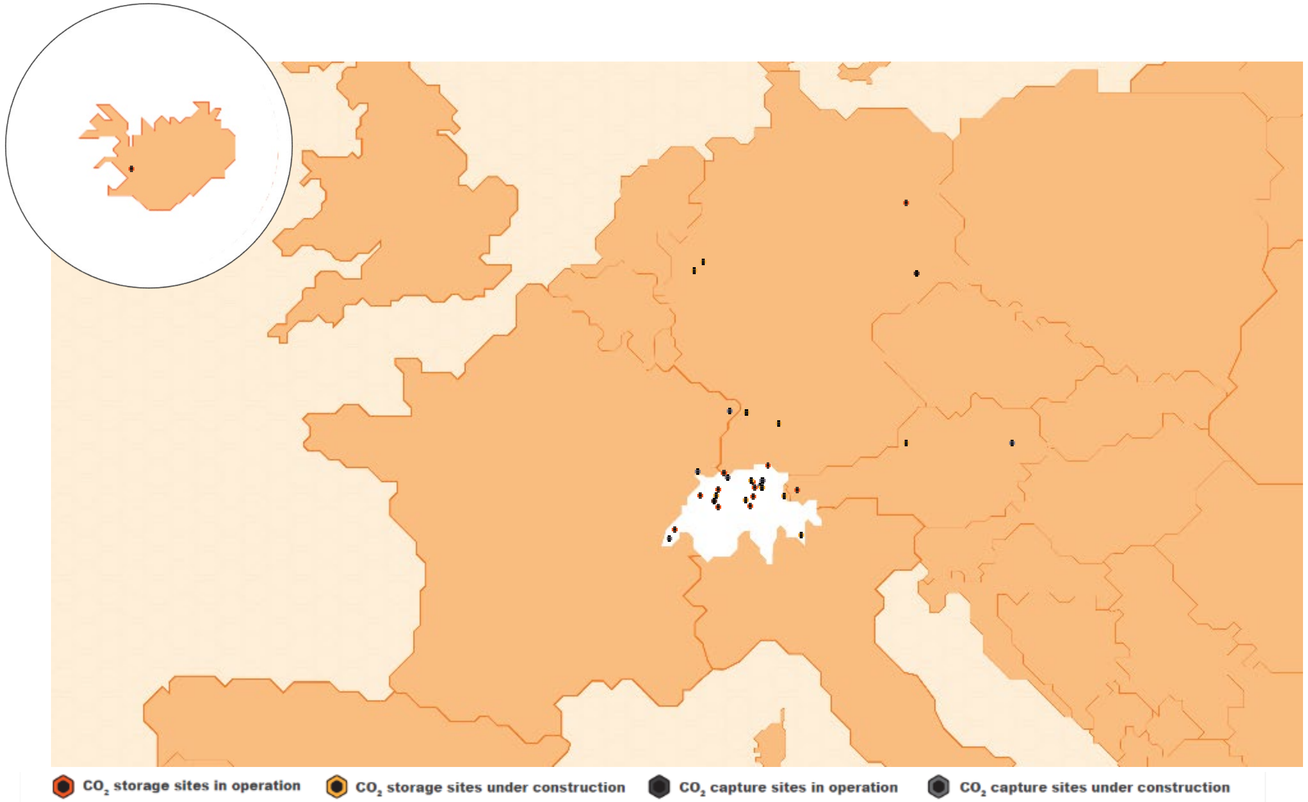
Take-aways:

- High throughput of BG (~mCO_2) drives costs down: operation is attractive for **large recyclers!**

- Profit expectation on CAPEX, reflected in payback, drives up costs: **CAPEX promotion** or **credit guarantees** help here

CO_2 storage in concrete is a business today!

- 12 storage sites already in operation + 20 more under construction
- 1st commercial CO_2 storage facility in the EU (Berlin) in operation
- Approx. 700 t CO_2 permanently removed from the atmosphere so far (and number growing exponentially)
- Scaling is progressing in big steps



Conclusion

Technology: Can it be integrated & scaled in today's industrial processes?	• 2 storage sites built, integrated into operation at Kästli, with >100 t CO_2 stored. • A total of around 30 systems sold
Material: Can the carbonated building material be used as before?	• Yes + can help to improve the compressive strength (concrete granulate) and workability (concrete slurry) of concrete mixtures.
Climate benefits: Does the solution save more emissions than it generates?	• Yes: efficiency >90% and emission savings possible in mixed design.
Economic viability: Can this solution be commercially viable (for all parties involved)?	• Yes, but profit expectations on capital and low throughputs drive costs strongly

CO_2 cross-border transport & permanent storage in the underground

David Yang Shu, ETH Zurich

Work package 3: Demonstration of CO_2 transport to a geological storage site

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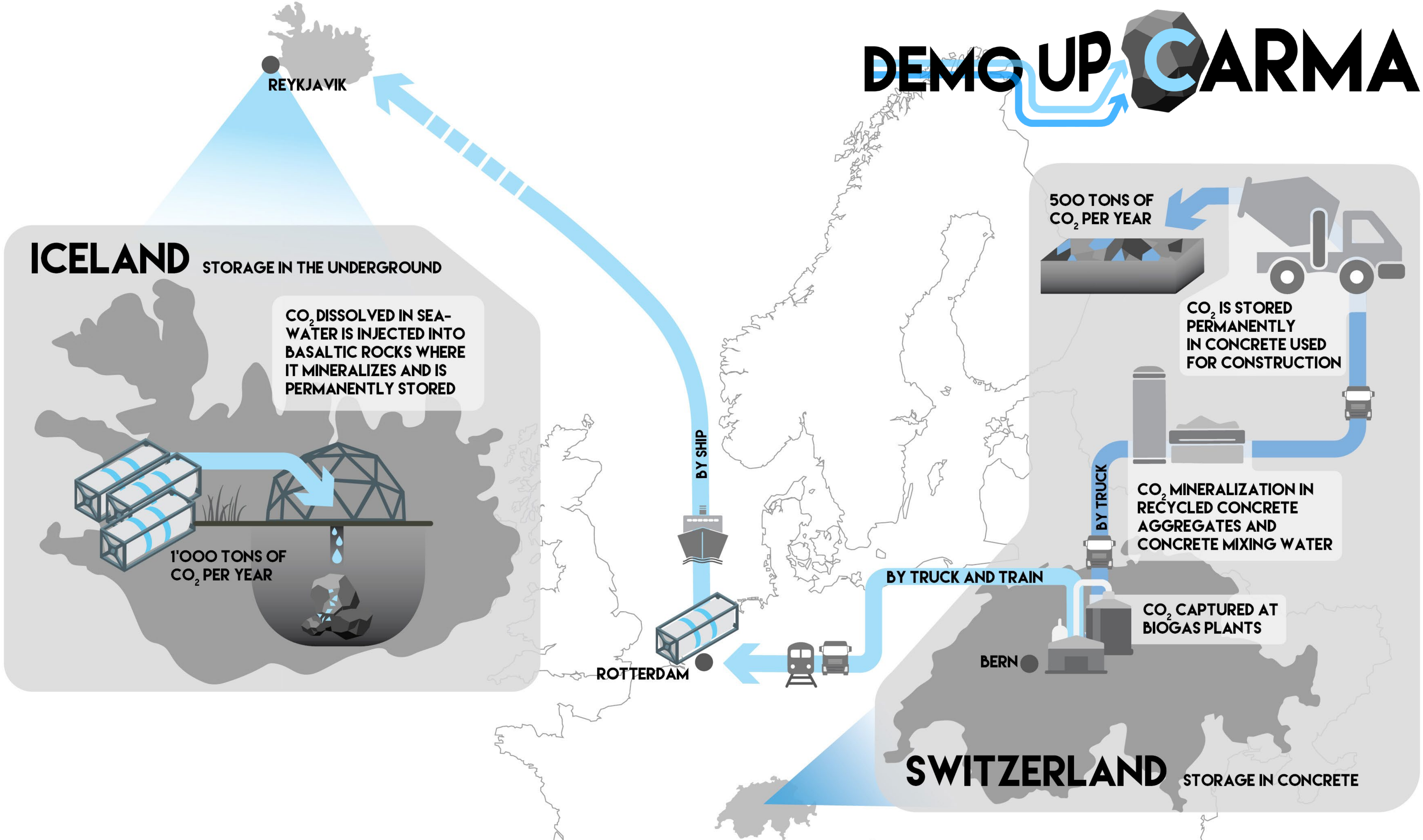
DEMO UPCARMA



ICELAND

STORAGE IN THE UNDERGROUND

CO_2 DISSOLVED IN SEA-WATER IS INJECTED INTO BASALTIC ROCKS WHERE IT MINERALIZES AND IS PERMANENTLY STORED

1'000 TONS OF CO_2 PER YEAR

500 TONS OF CO_2 PER YEAR

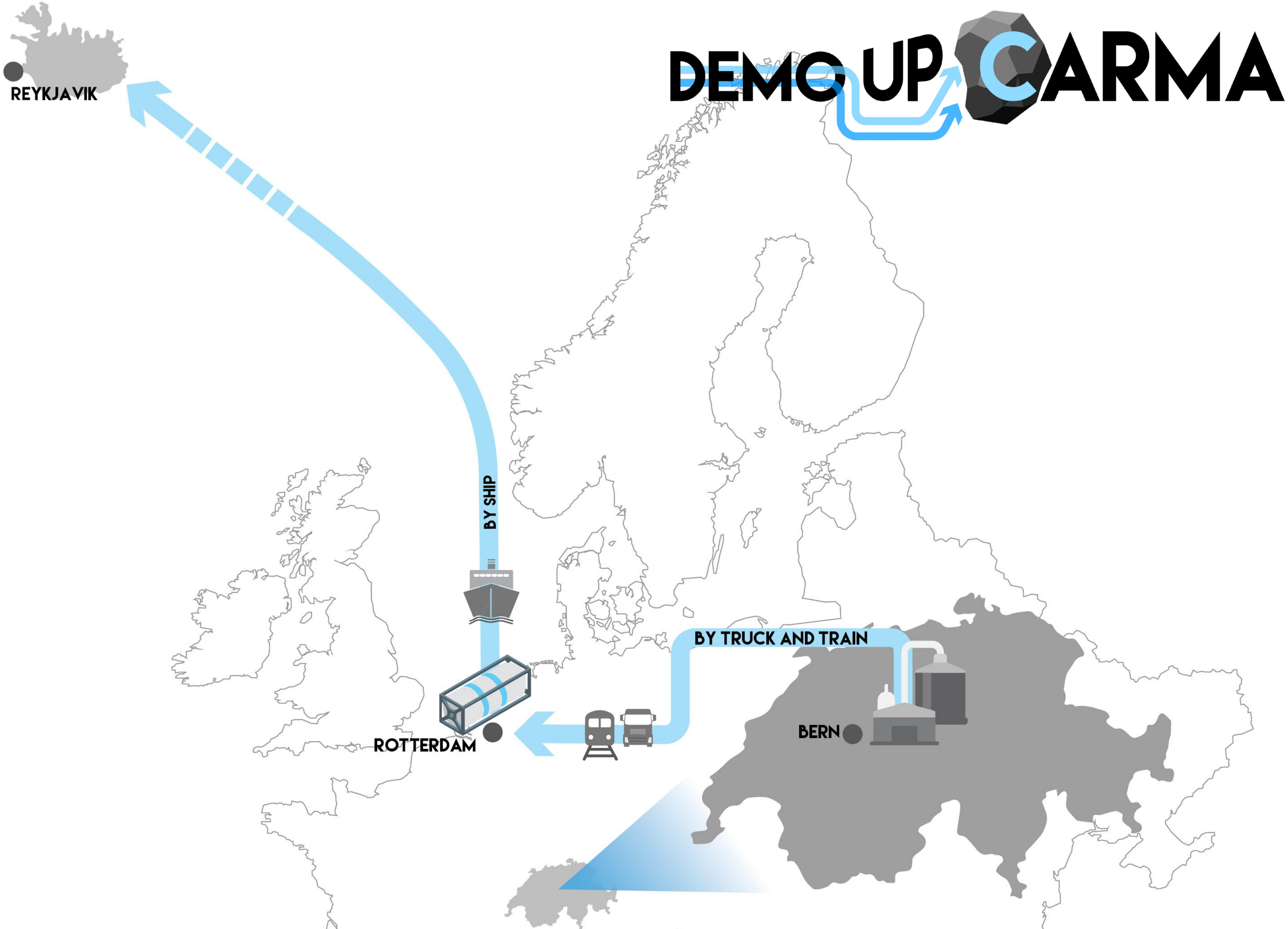
CO_2 IS STORED PERMANENTLY IN CONCRETE USED FOR CONSTRUCTION

CO_2 MINERALIZATION IN RECYCLED CONCRETE AGGREGATES AND CONCRETE MIXING WATER

CO_2 CAPTURED AT BIOGAS PLANTS

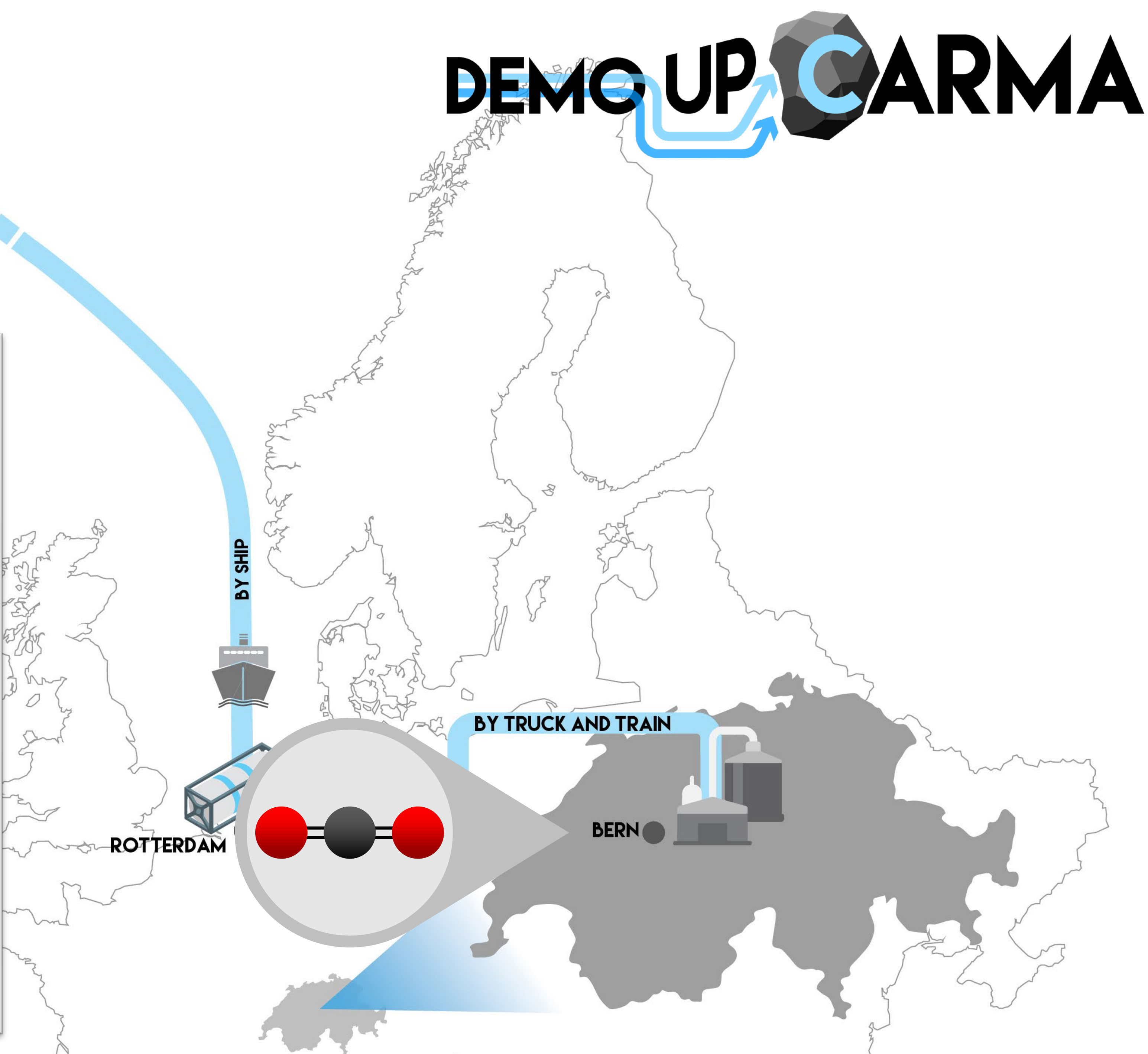
SWITZERLAND

STORAGE IN CONCRETE


DEMO UP CARMA
REYKJAVIK
BY SHIP
ROTTERDAM
BY TRUCK AND TRAIN
BERN

DEMO UP CARMA

day 1



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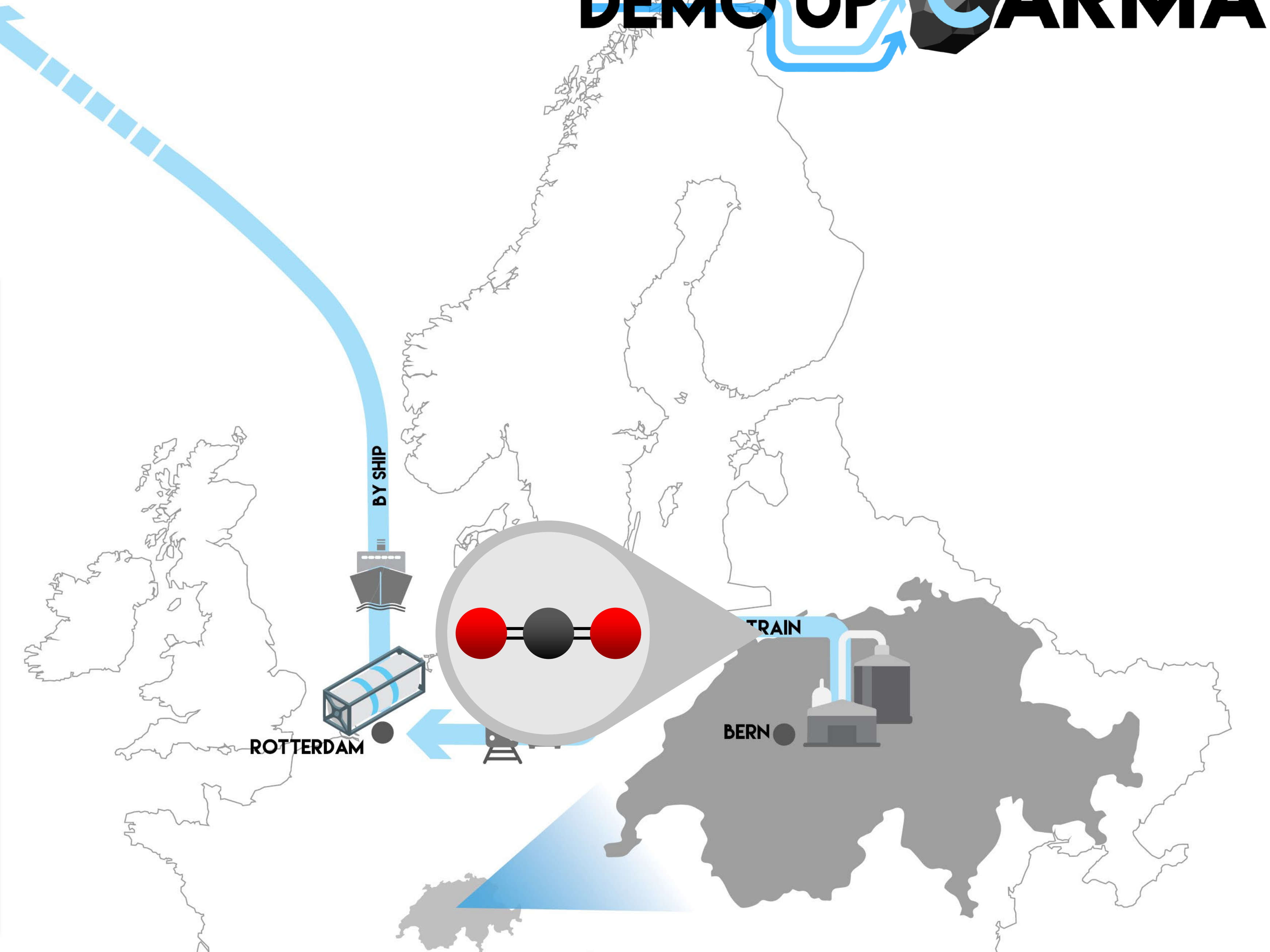
day 2



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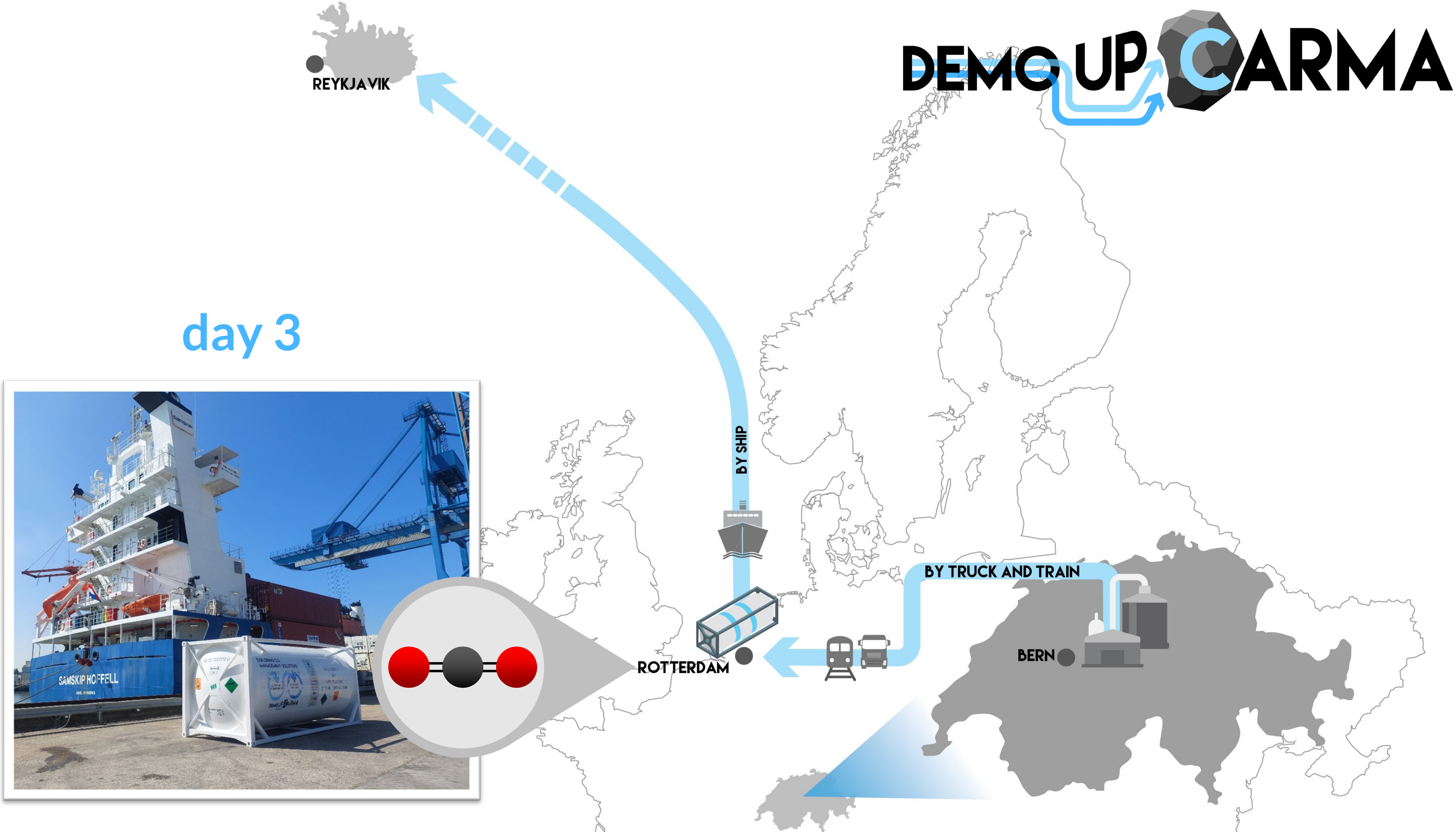
day 3



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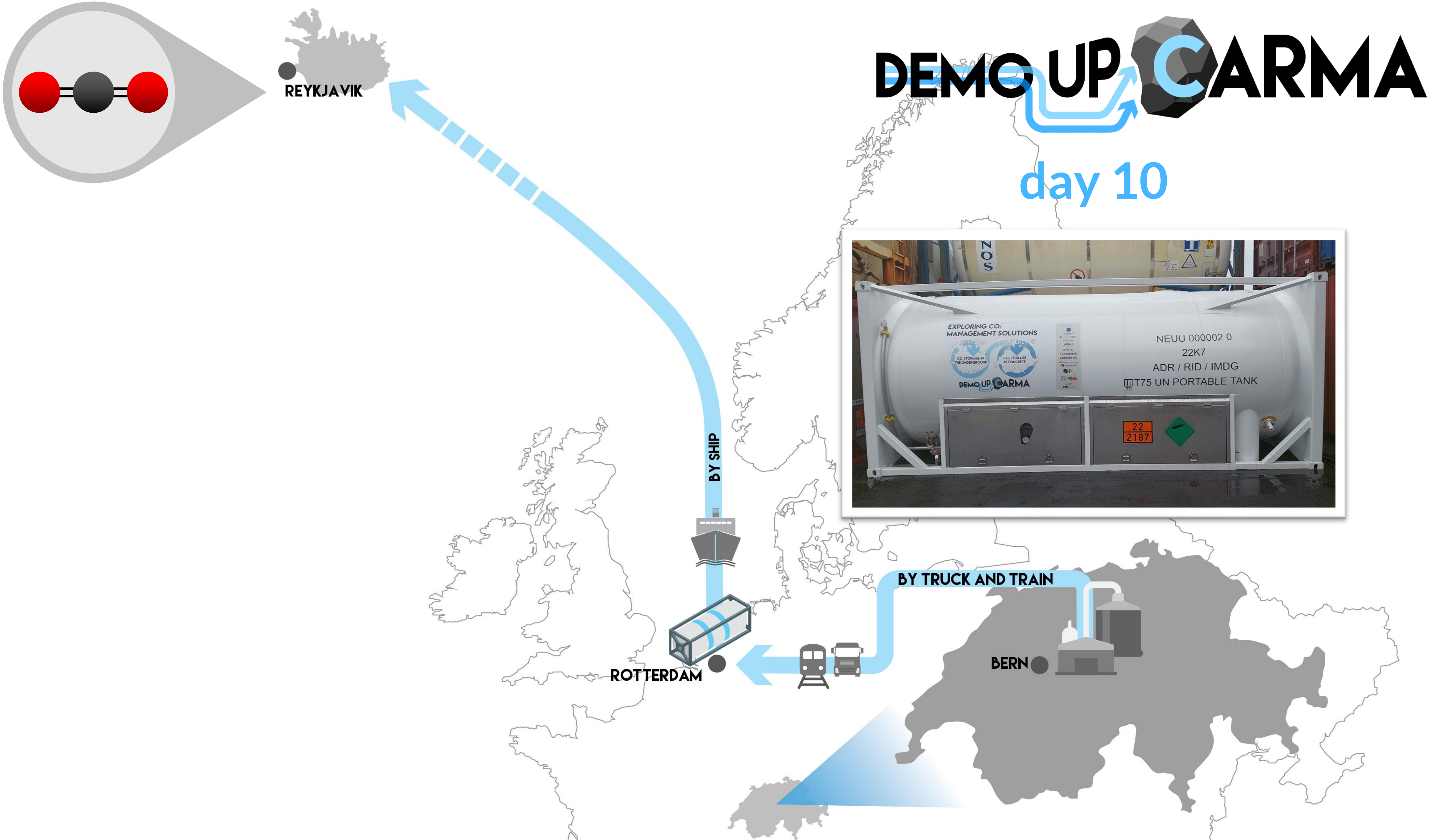
day 10



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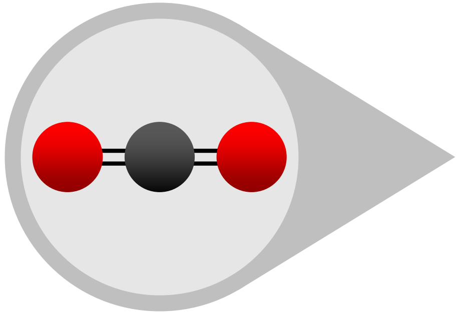
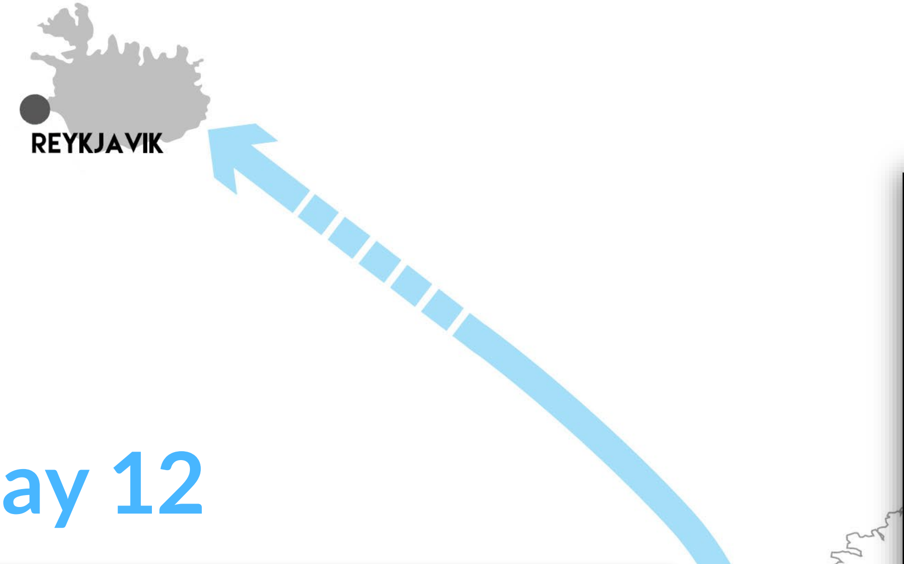
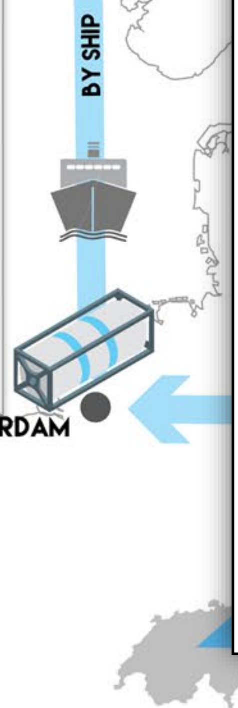
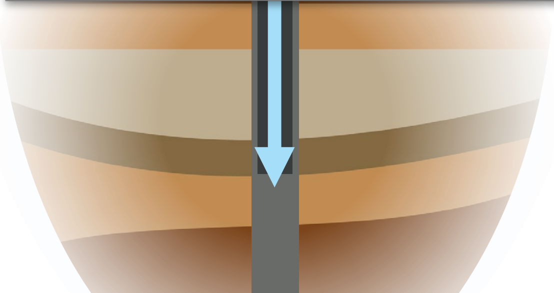




day 12





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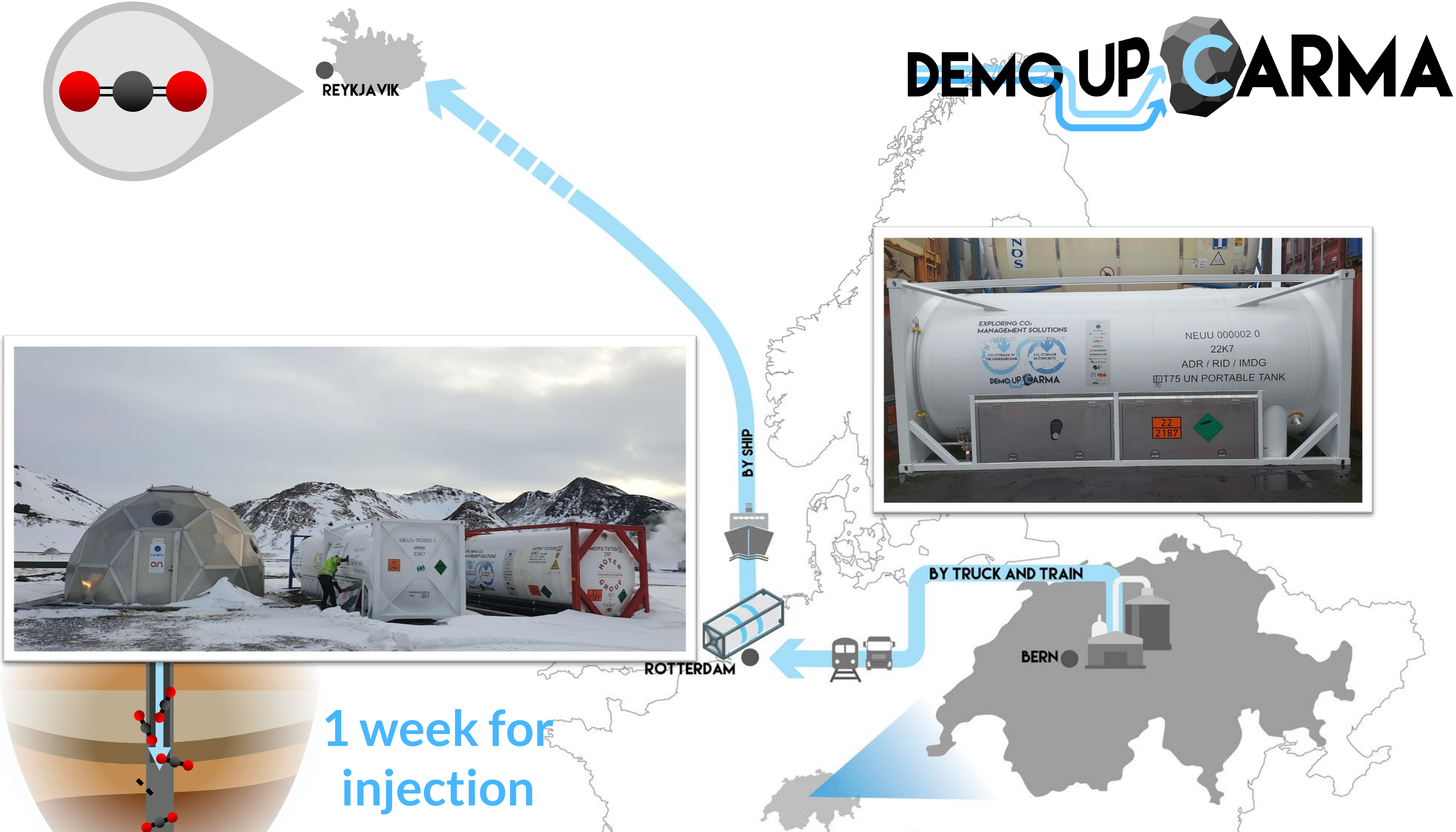
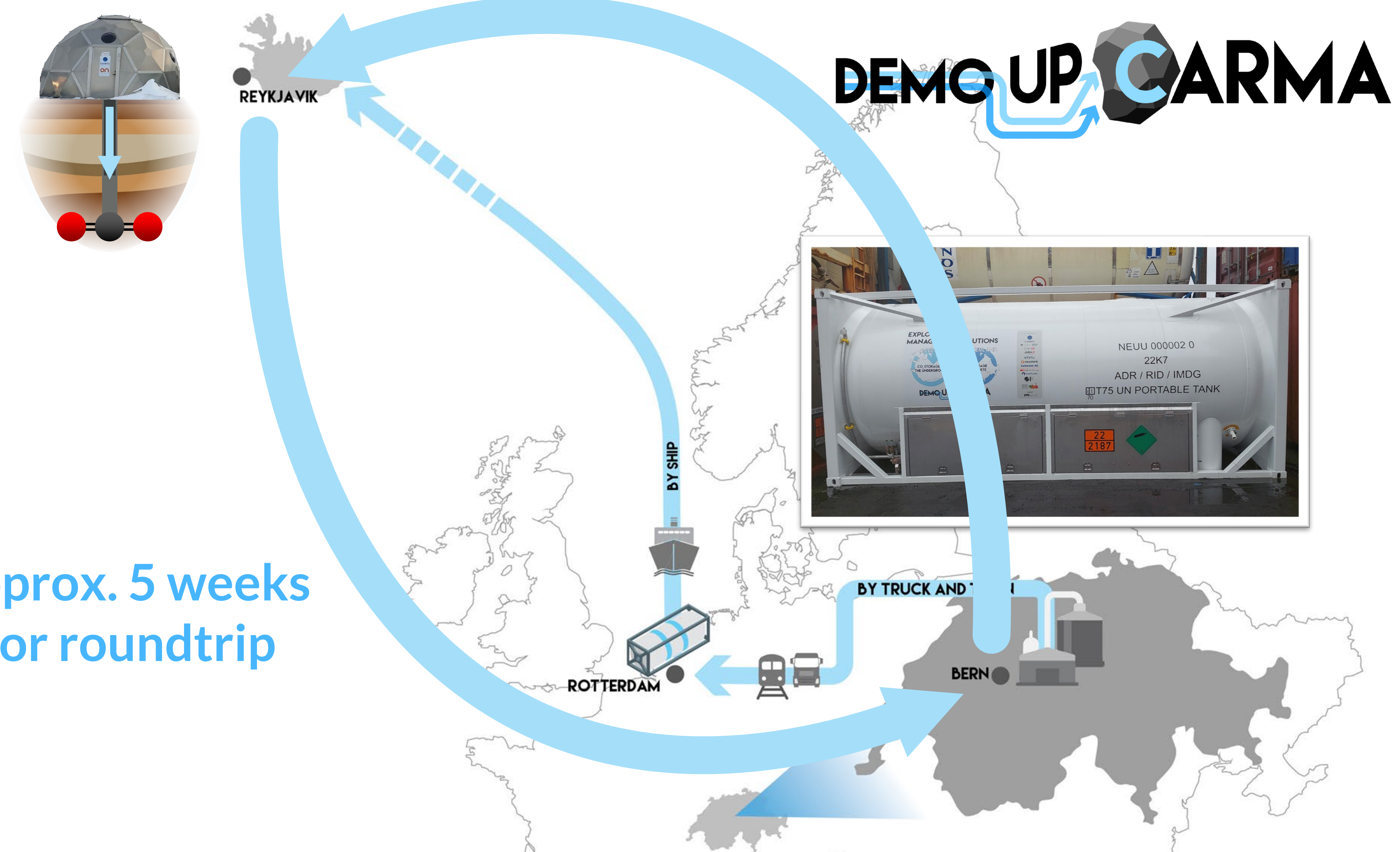


1 week for injection

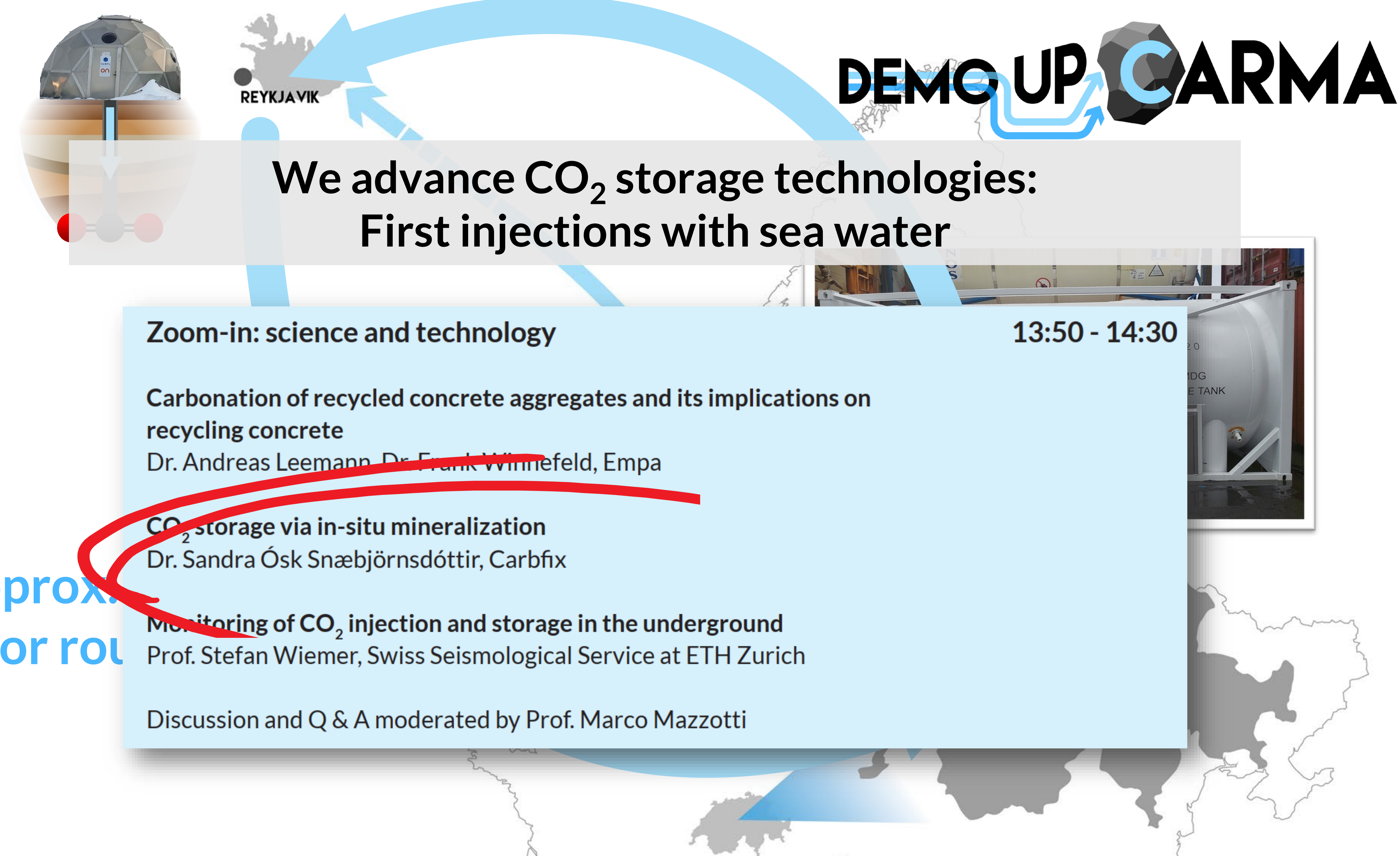
DEMO UPCARMA



approx. 5 weeks
for roundtrip

DEMO UPCARMA

We advance CO_2 storage technologies: First injections with sea water



Zoom-in: science and technology **13:50 - 14:30**

Carbonation of recycled concrete aggregates and its implications on recycling concrete
Dr. Andreas Leemann, Dr. Frank Winnefeld, Empa

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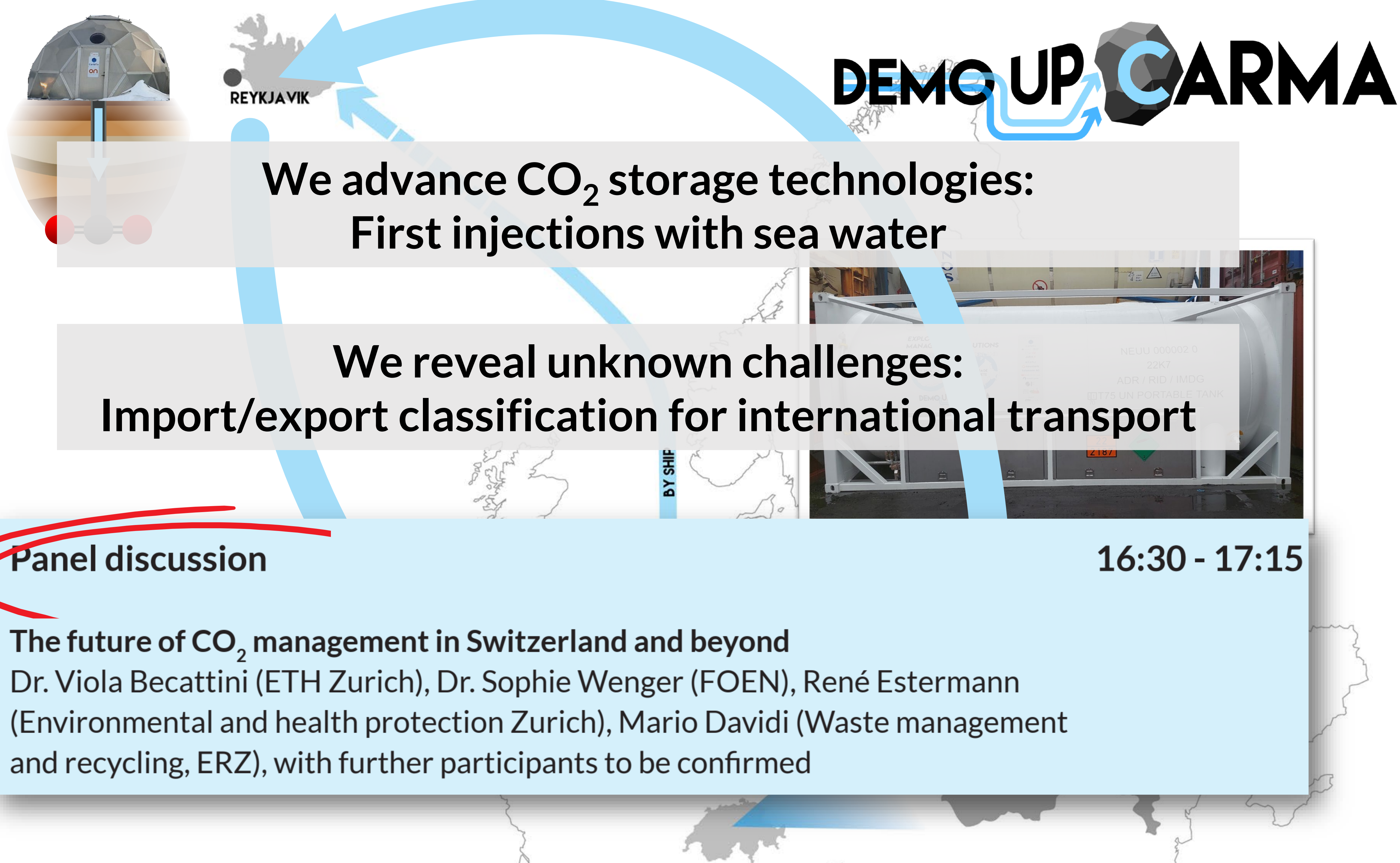
approx.
for rou



DEMO UP CARMA

We advance CO_2 storage technologies: First injections with sea water

We reveal unknown challenges: Import/export classification for international transport

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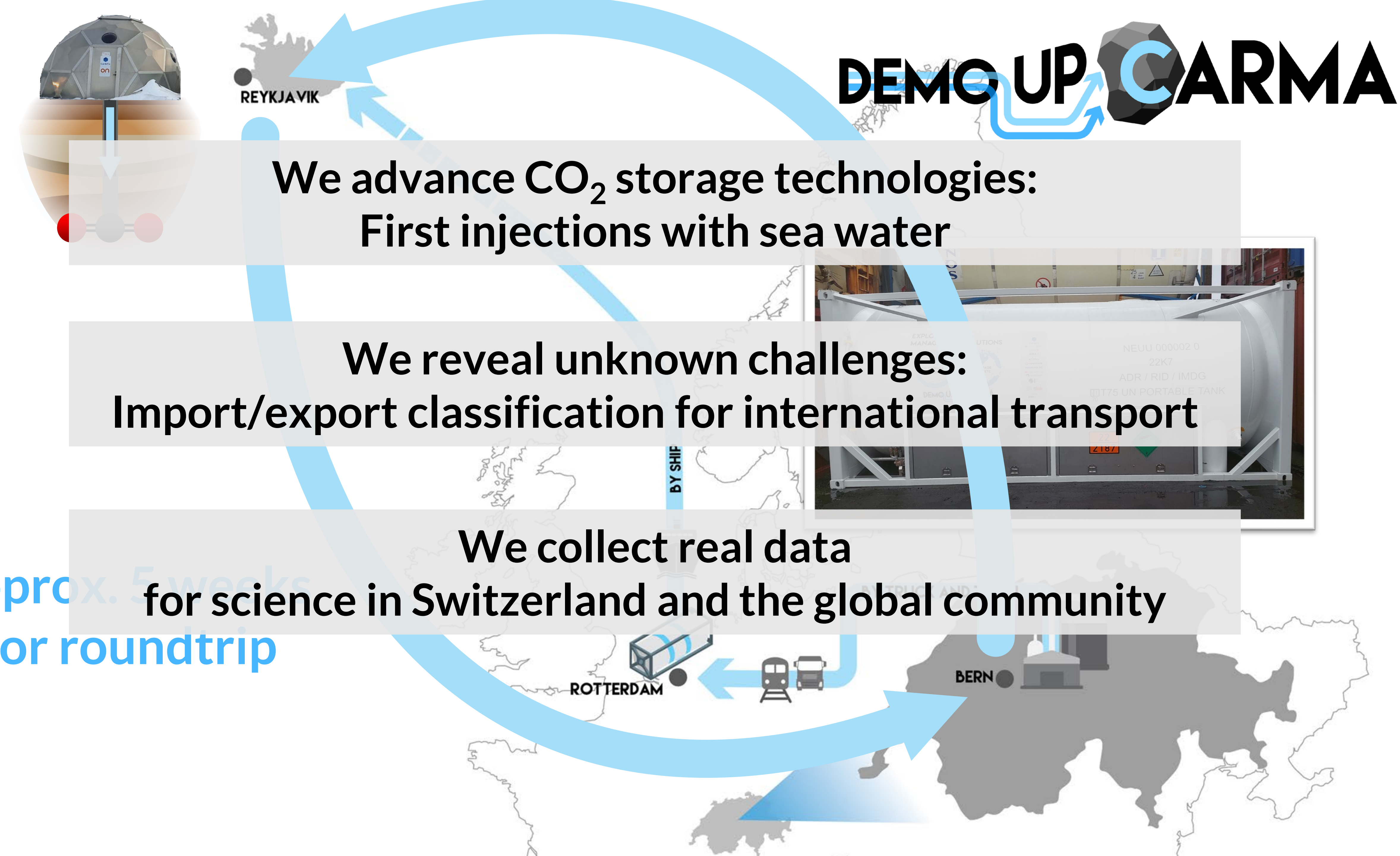
Panel discussion 16:30 - 17:15

The future of CO_2 management in Switzerland and beyond

Dr. Viola Becattini (ETH Zurich), Dr. Sophie Wenger (FOEN), René Estermann (Environmental and health protection Zurich), Mario Davidi (Waste management and recycling, ERZ), with further participants to be confirmed

DEMO UPCARMA



approx. 5 weeks
for roundtrip

We advance CO_2 storage technologies:
First injections with sea water

We reveal unknown challenges:
Import/export classification for international transport

We collect real data
for science in Switzerland and the global community

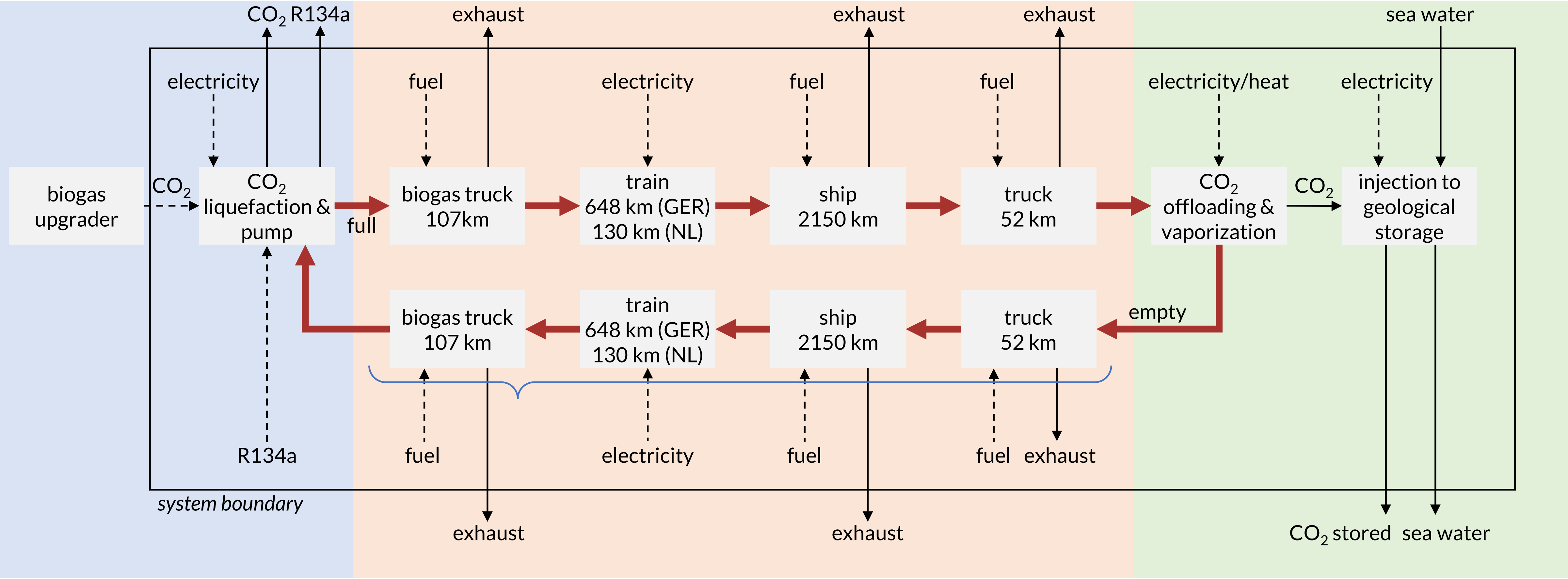

REYKJAVIK
BY SHIP
ROTTERDAM
BY TRUCK AND T N
BERN


J. Burger


J. Nöhl


J. Seiler

Environmental impacts of storing CO_2 from Bern in Helguvík


CO_2 R134a

exhaust

exhaust

exhaust

sea water

electricity

fuel

electricity

fuel

fuel

electricity/heat

electricity

biogas upgrader

CO_2

CO_2 liquefaction & pump

full

biogas truck 107km

train 648 km (GER) 130 km (NL)

ship 2150 km

truck 52 km

CO_2 offloading & vaporization

CO_2

injection to geological storage

empty

biogas truck 107 km

train 648 km (GER) 130 km (NL)

ship 2150 km

truck 52 km

R134a

fuel

electricity

fuel

fuel

exhaust

system boundary

exhaust

exhaust

CO_2 stored

sea water

transport iso-container

product flow

elementary flow


J. Burger


J. Nöhl


J. Seiler

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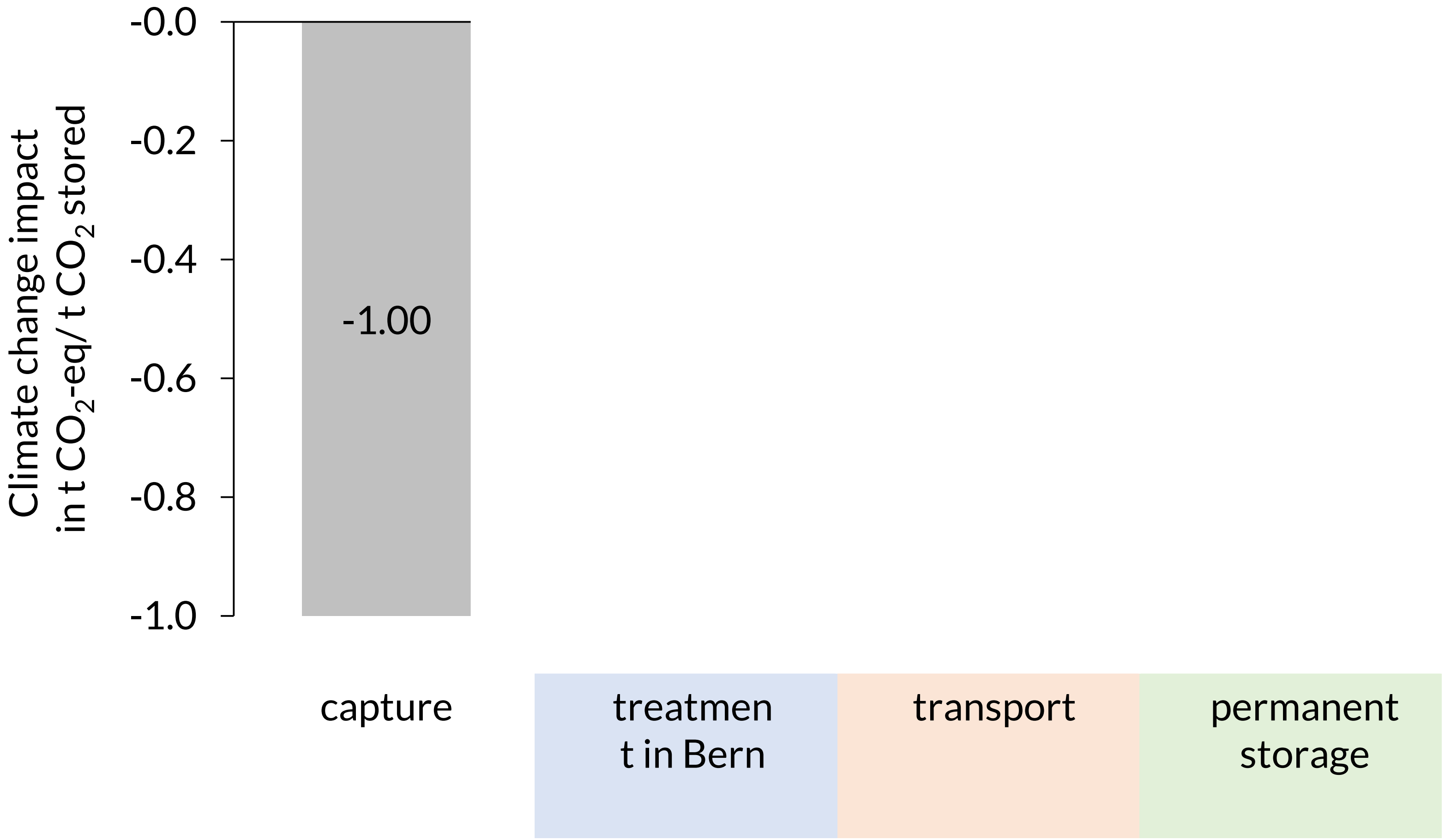

DEMO UP CARMA


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J. Nöhl


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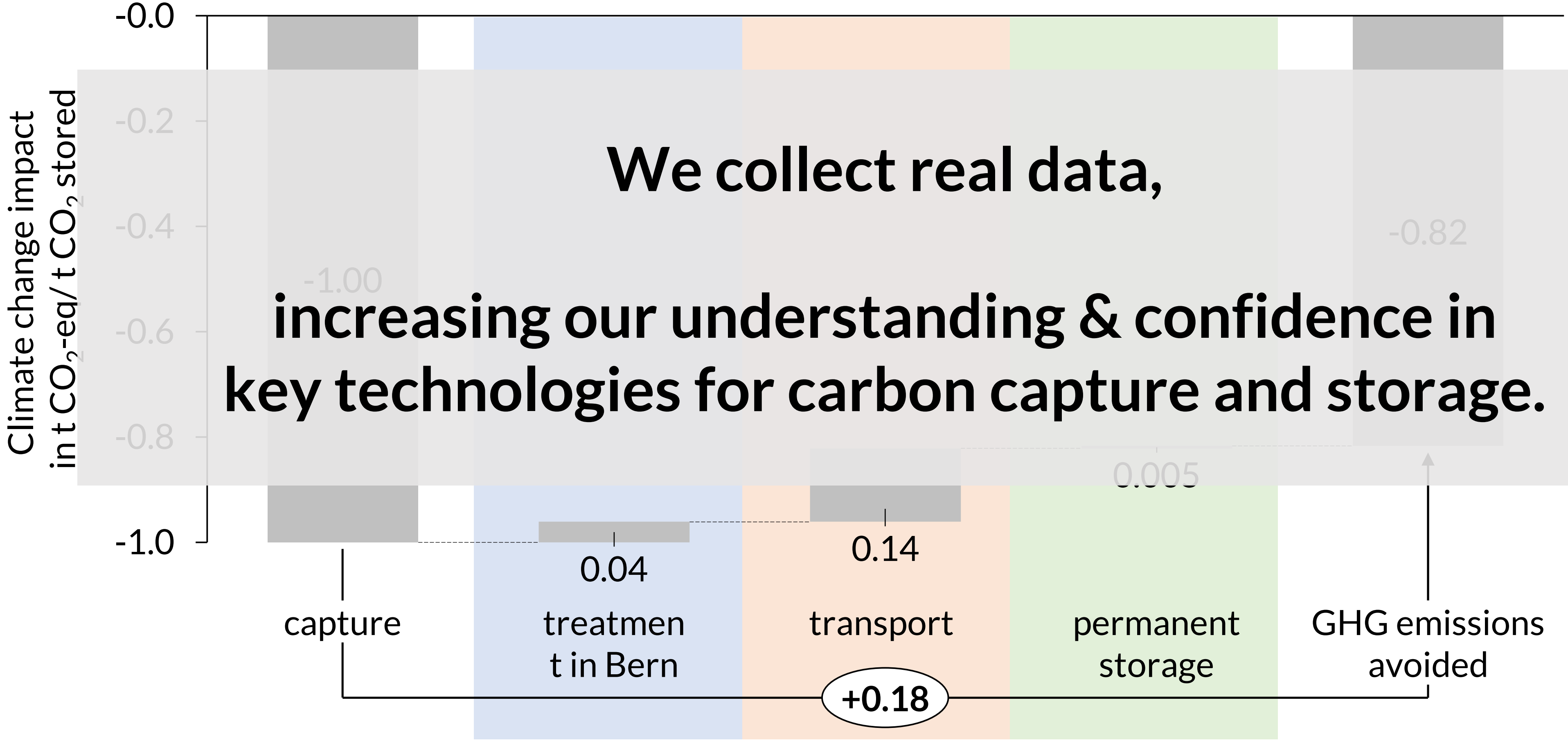


We collect real data,

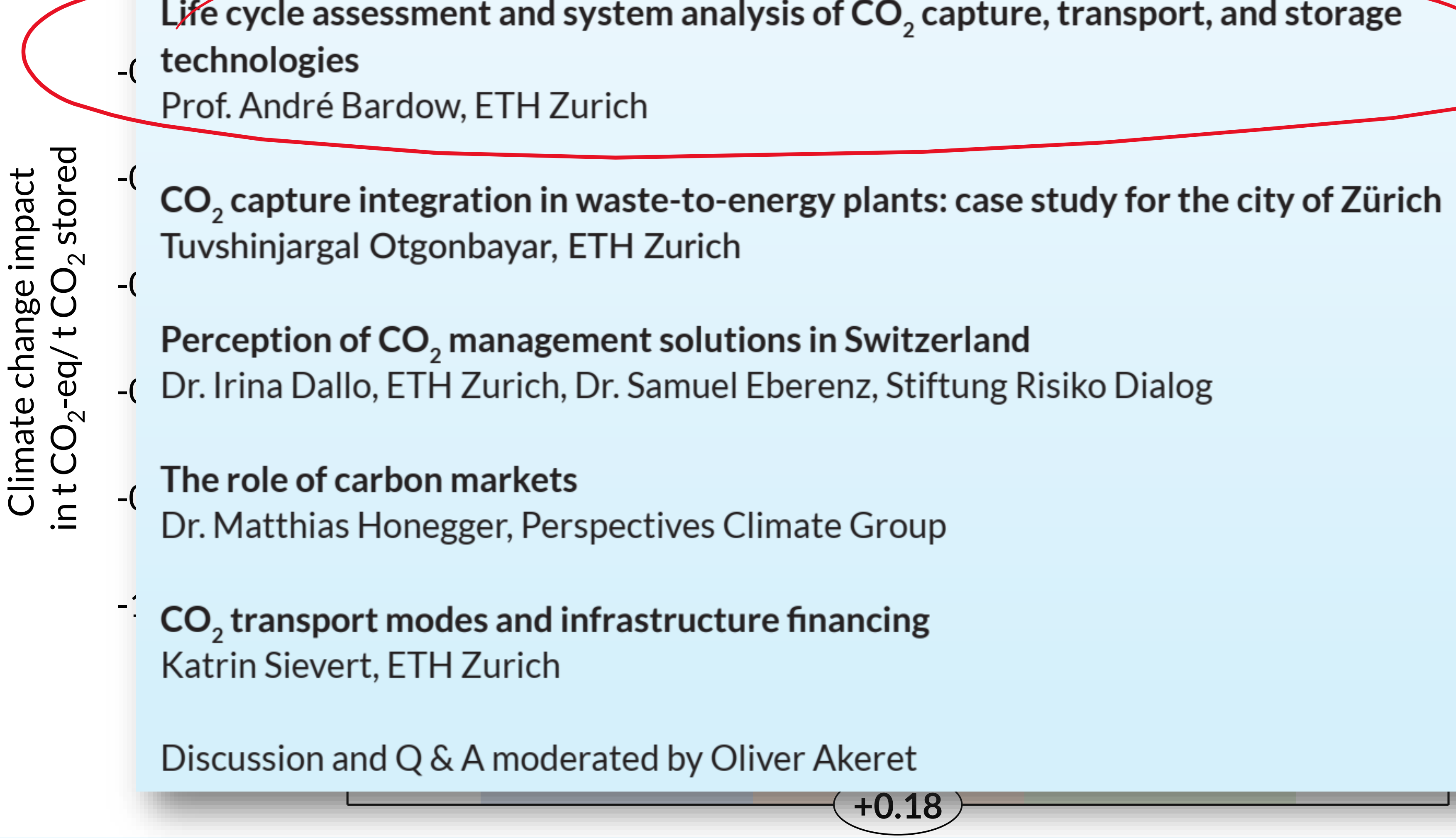
increasing our understanding & confidence in key technologies for carbon capture and storage.

DEMO UP CARMA

Nöhl

J. Seiler

Enviror



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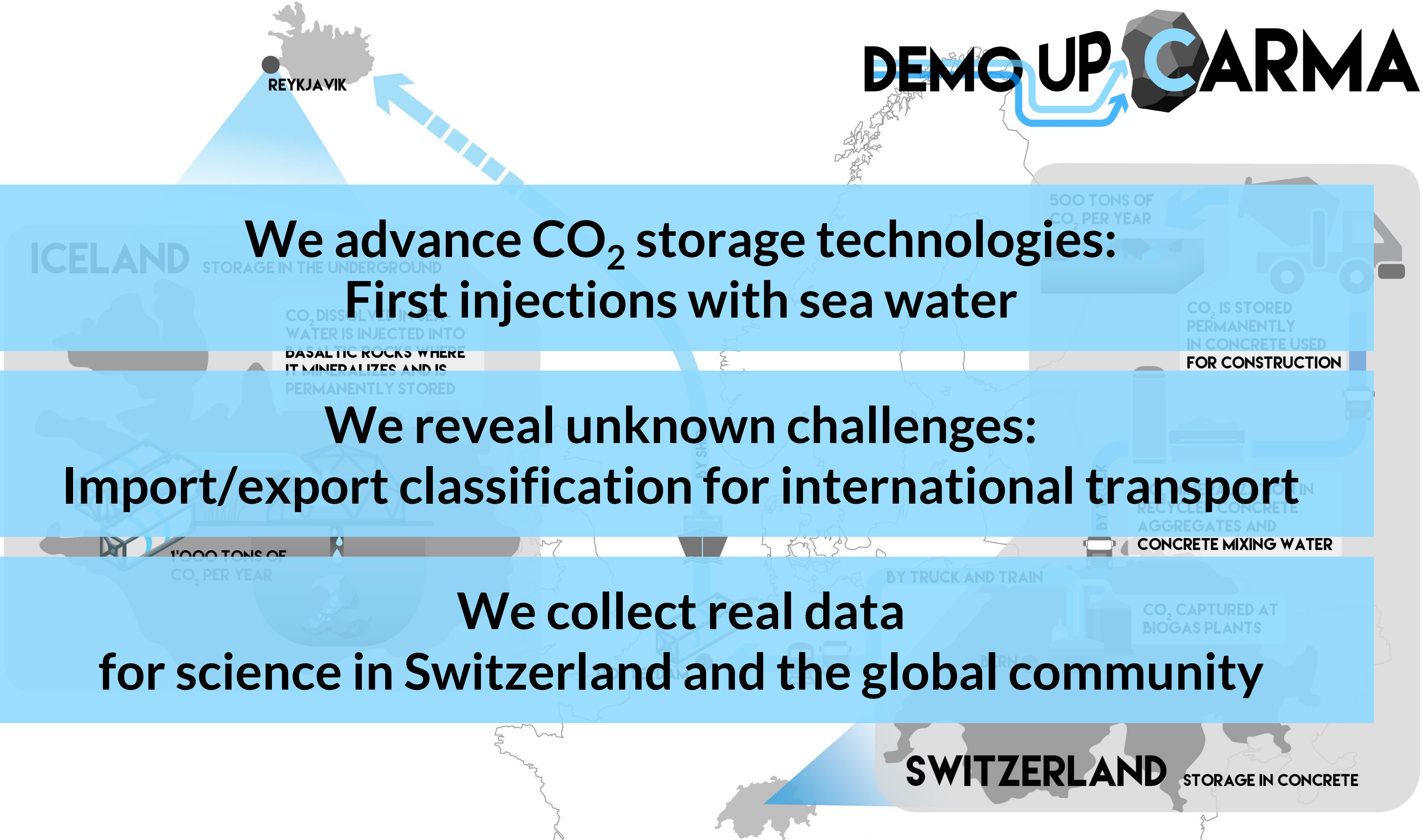
DEMO UPCARMA



We advance CO$_2$ storage technologies:
First injections with sea water

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We collect real data
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Zoom-in: science and technology

ETH zürich

DEMO UP CARMA

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

Dr. Andreas Leemann, Dr. Frank Winnefeld

Empa
Materials Science and Technology

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Swiss Federal Office of Energy SFOE

Federal Office for the Environment FOEN

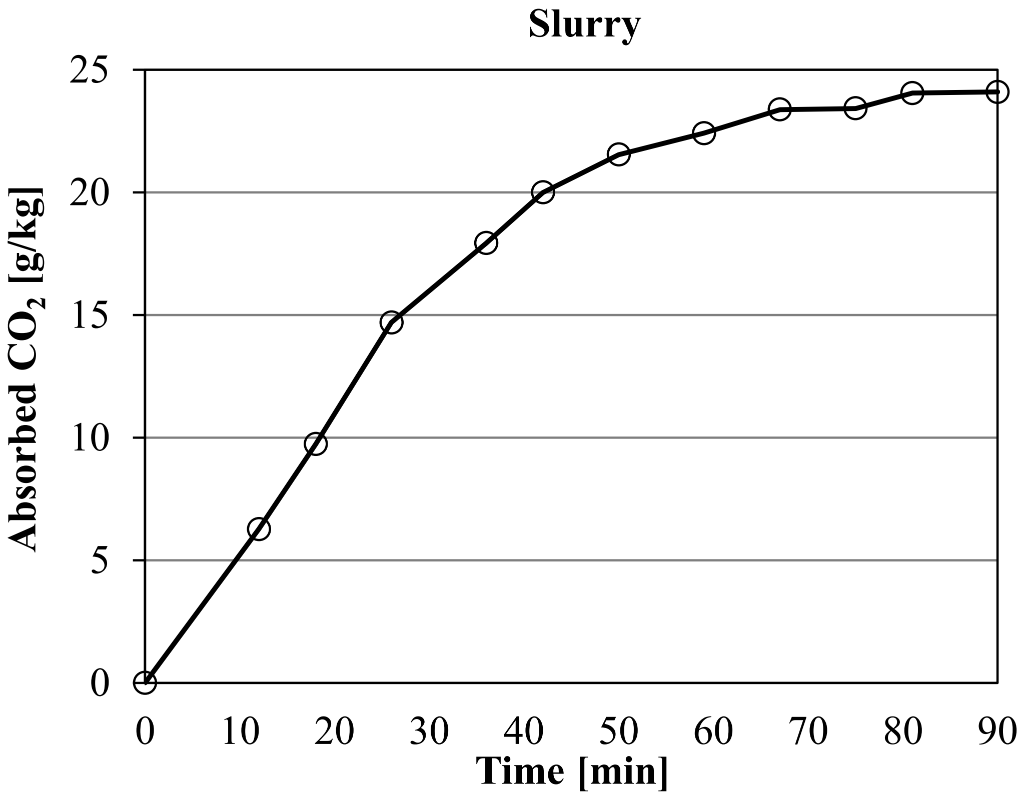
Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

Content

- Slurry
  - CO_2 absorption
  - Effect on concrete properties
- Recycled concrete aggregates (RCA)
  - CO_2 absorption
  - Effect on concrete properties
  - Microstructure of carbonated RCA
- Summary

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

Slurry: CO_2 absorption



- Fast CO_2 absorption by slurry
- Amount of absorbed CO_2 as determined with thermogravimetry: ~ 14 g CO_2/l of slurry, may vary with density of slurry
- Products formed: calcite ($CaCO_3$), gypsum and decalcified calcium-silicate-hydrate (C-S-H)

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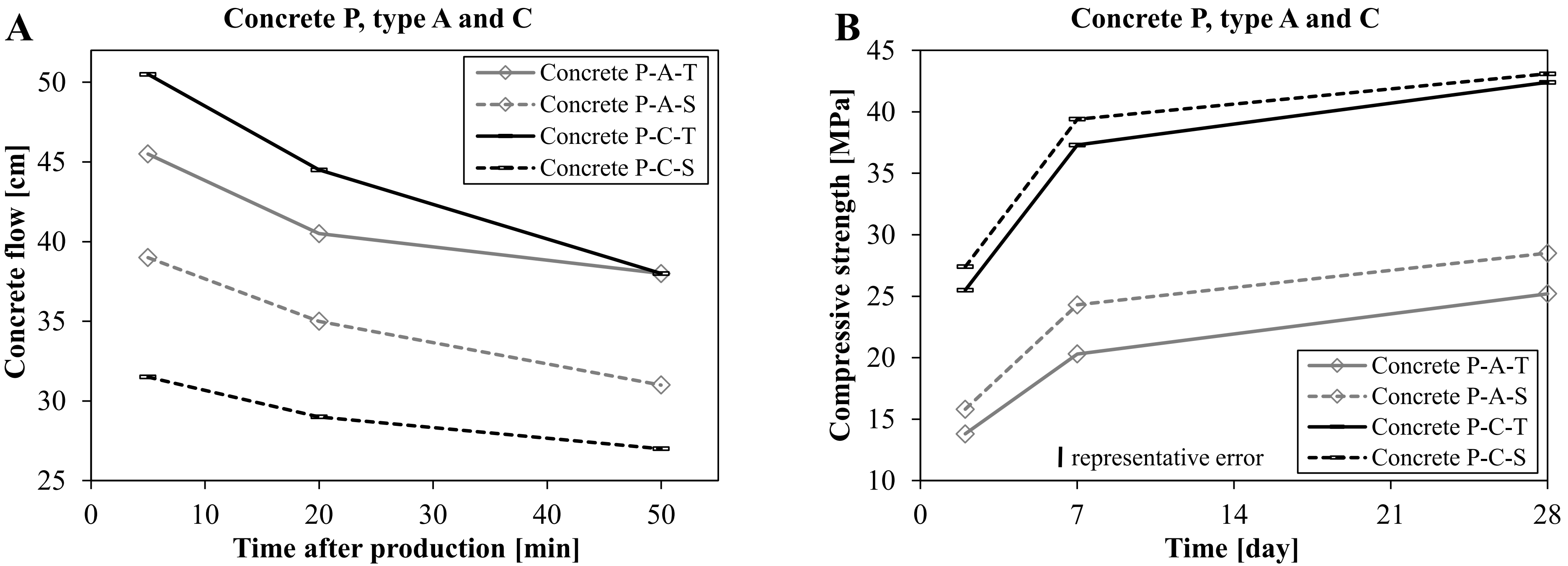
Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

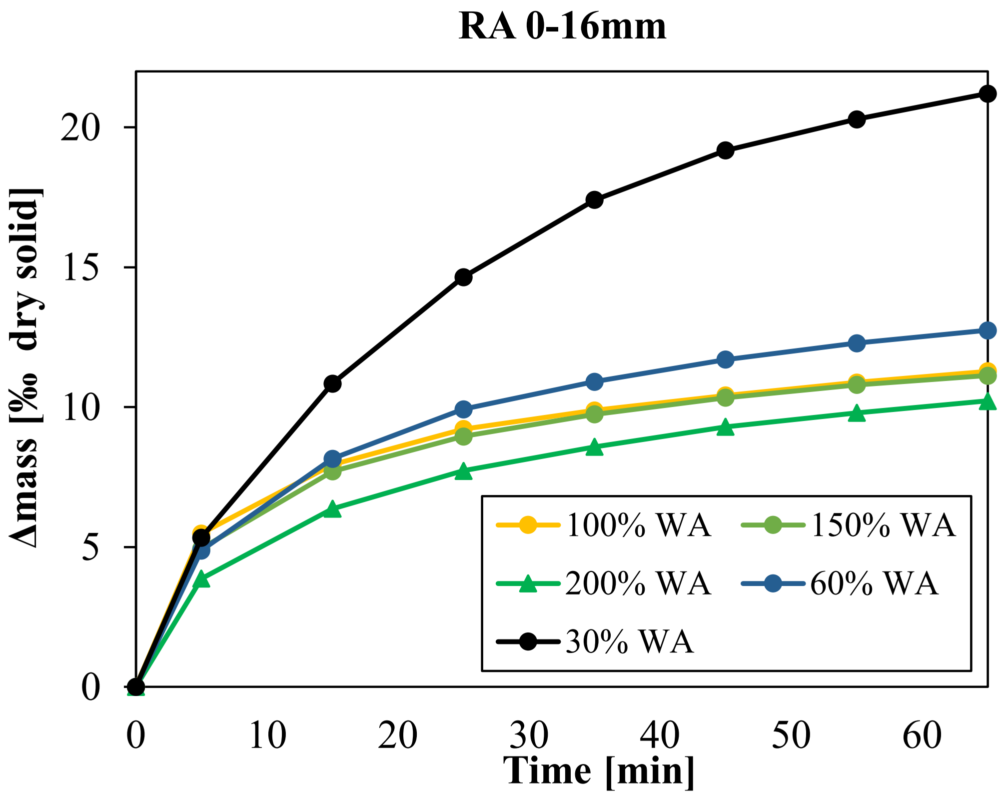
Slurry combined with natural aggregates for concrete production (concrete P)



- Slurry causes loss of workability (applies as well to concrete with RCA) → dosage of superplasticizer to be increased (adds CO_2 emission of about 1% in relation to emission of cement)
- Slurry causes increase of compressive strength (no increase in concrete with RCA)
- Effect of carbonated slurry on workability less pronounced compared to uncarbonated slurry

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

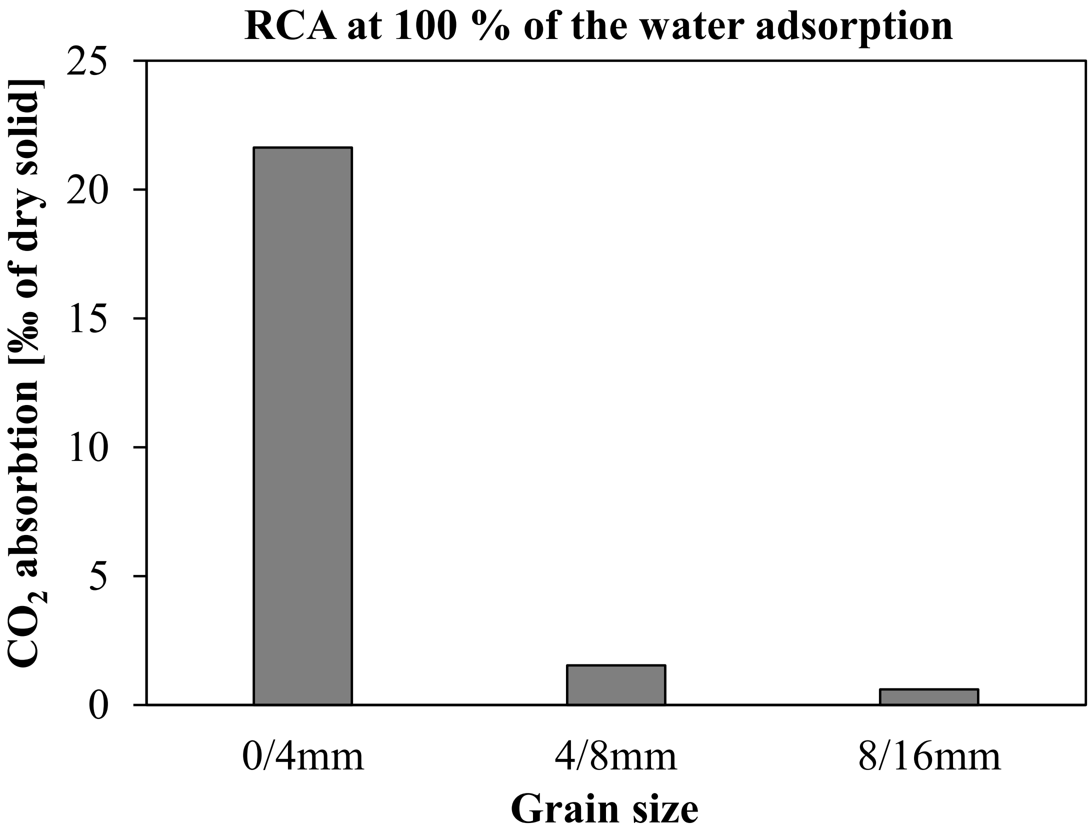
RCA: CO_2 absorption at different moisture levels (state of delivery: 115% of water adsorption WA_{24})



- Little variation of CO_2 absorption between 60-200 % of WA_{24} (~11 kg CO_2/t of RCA)
- Significant increase of CO_2 absorption only at low moisture level ≤ 30 % WA_{24}
- Low moisture level (~30% RH) usually not achievable in concrete plant

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

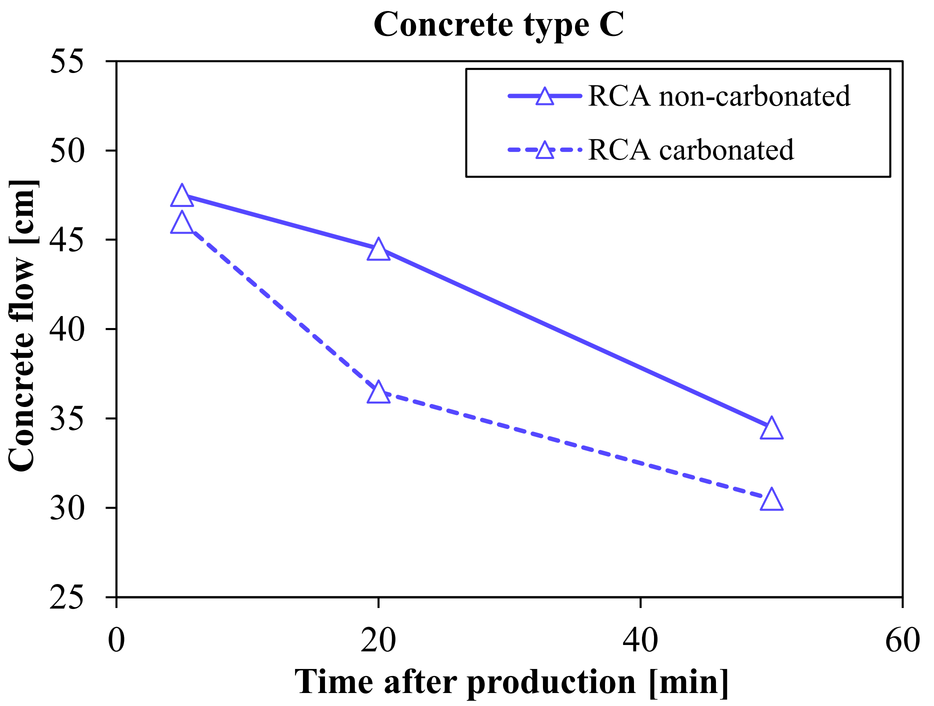
RCA: CO_2 absorption of different grain size classes (100% WA_{24})

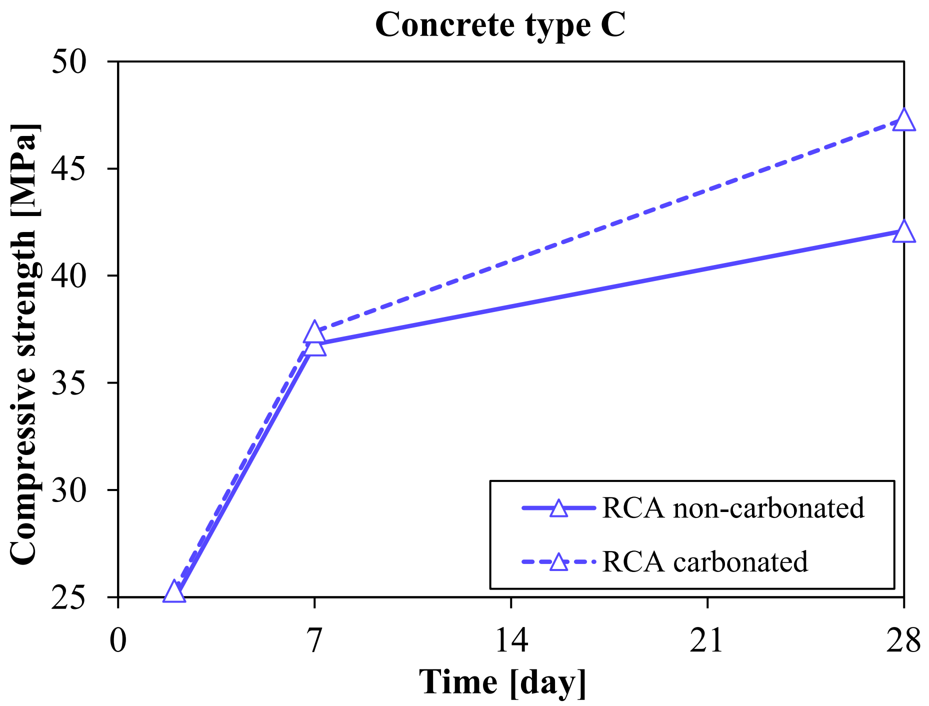


- Highest absorption by sand 0/4 mm
- Highest surface area in sand
  → Indication of reaction limited to particle surface

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

RCA: Recycling concrete with 60 mass-% of RCA

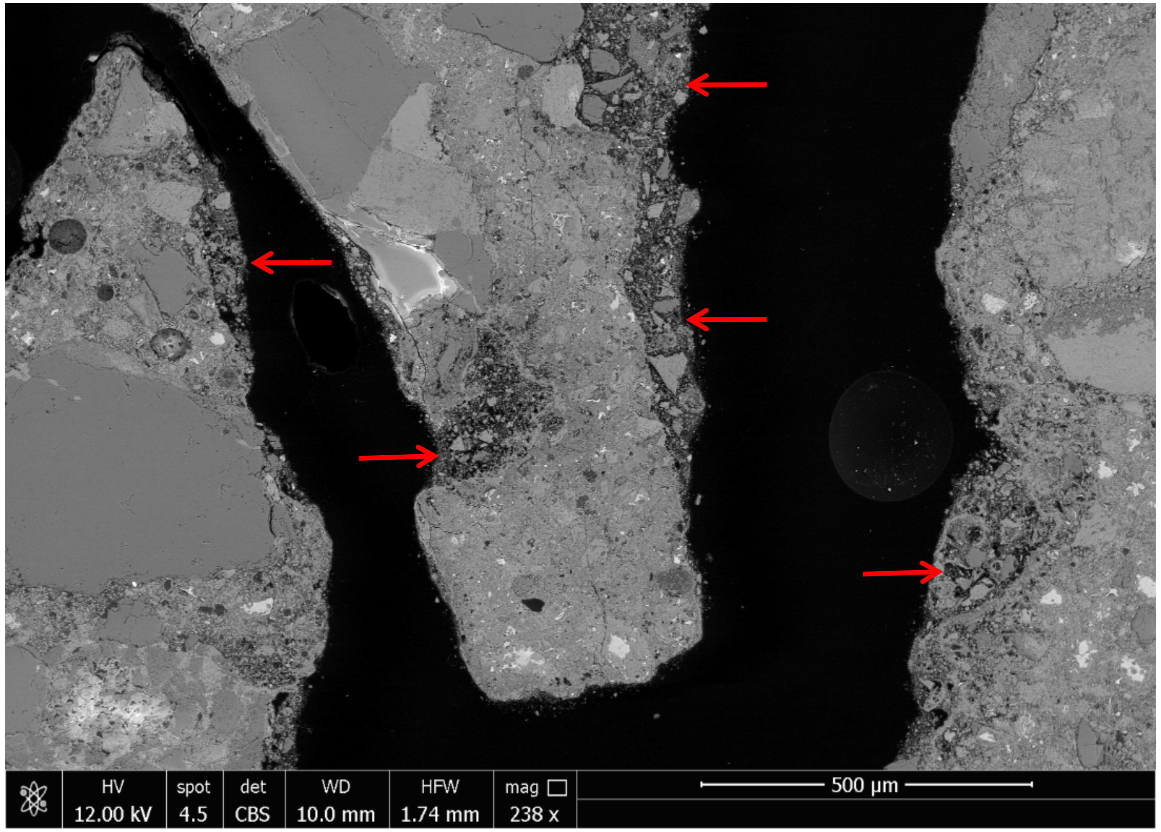




- Carbonated RCA causes faster loss of workability → use of a flow stabilizer
- Carbonated RCA increases compressive strength → potential for cement reduction

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

RCA: effect of accelerated carbonation on microstructure

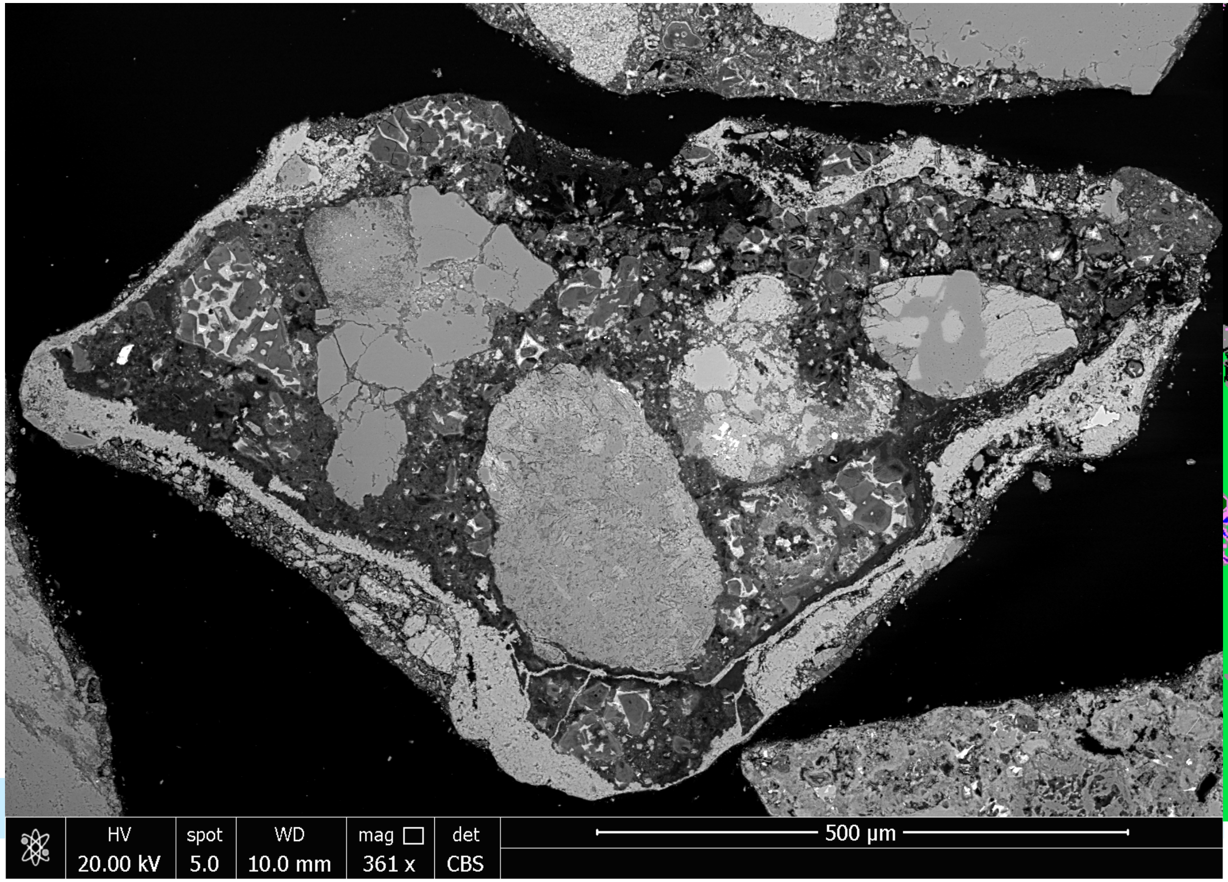


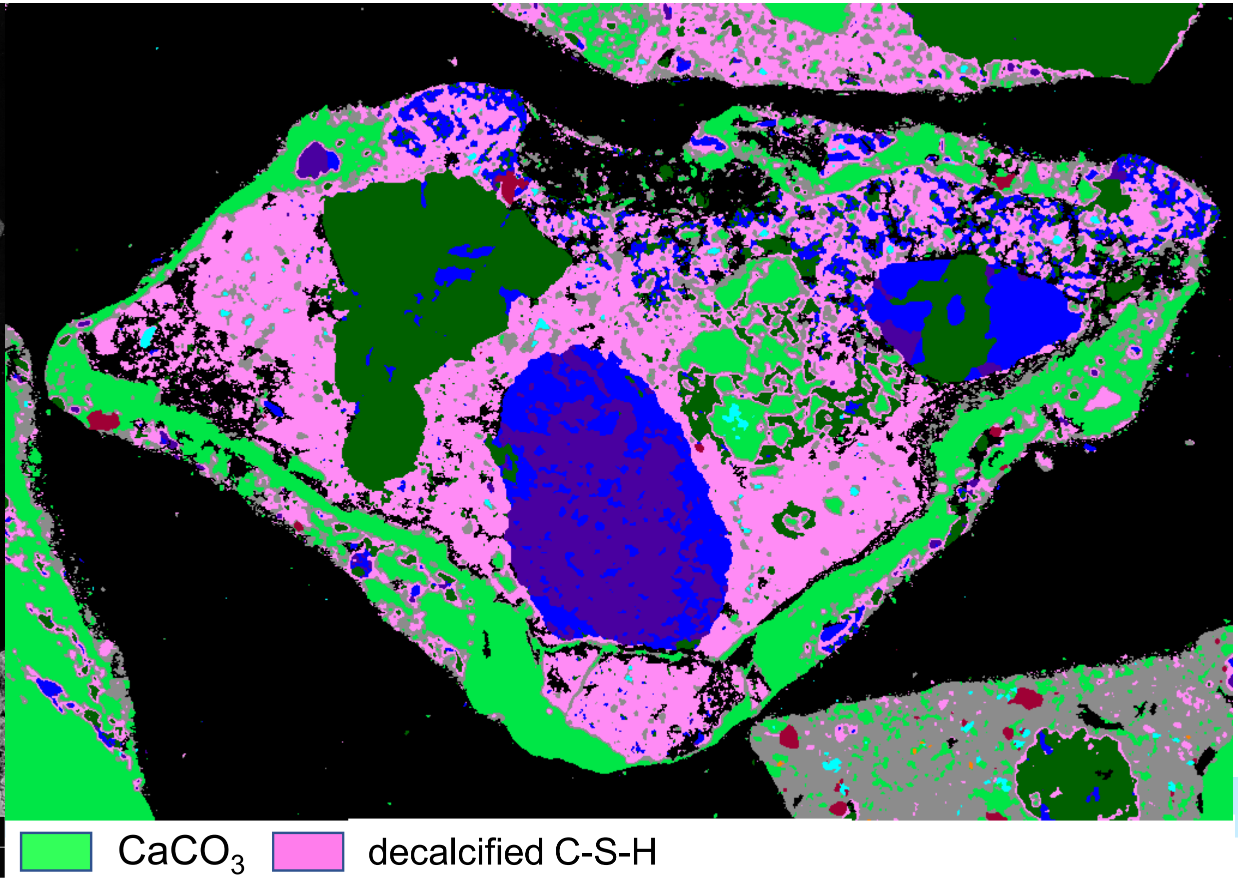
- Alterated patches highly variable in thickness from non-existing to a maximum of 300 µm on surface of particles

Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

RCA: effect of accelerated carbonation on microstructure

- Formation of $CaCO_3$ layer (non-reactive) and decalcified C-S-H (reactive)
- Decalcified C-S-H reacts with portlandite and forms additional C-S-H → strength increase





Demonstration of CO_2 utilization and storage in concrete: Assessment of concrete mix designs

Summary

- Slurry
  - Slurry can absorb ~ 14 g of CO_2/liter (depending on amount of suspended fines)
  - Use of uncarbonated and carbonated wet slurry requires a small adaption of mix design (more superplasticizer to counteract workability loss)
- RCA
  - RCA 0-16 mm absorbs ~ 11 kg CO_2/t, mainly in the fines
  - CO_2 absorption of RCA would be increased at a lower moisture content
  - Accelerated carbonation leads to the formation of reactive decalcified C-S-H
  - Implications of carbonated RCA on workability of fresh concrete can be overcome with common measures
  - Compressive strength of concrete with carbonated RCA is increased
  - Use of carbonated RCA has the benefit of CO_2 absorption and potential cement reduction

Carbfix

CO_2 turned to stone

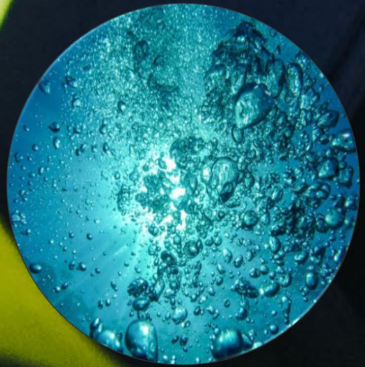
Carbfix turns captured CO_2 into stone underground in less than two years through a proprietary technology that imitates and accelerates natural processes

Basalts and other reactive rock formations

$Ca^{2+}, Mg^{2+}, Fe^{2+}{}_{(aq)}$

+

CO_2 dissolved in water



$CO_3{}^{2-}{}_{(aq)}$

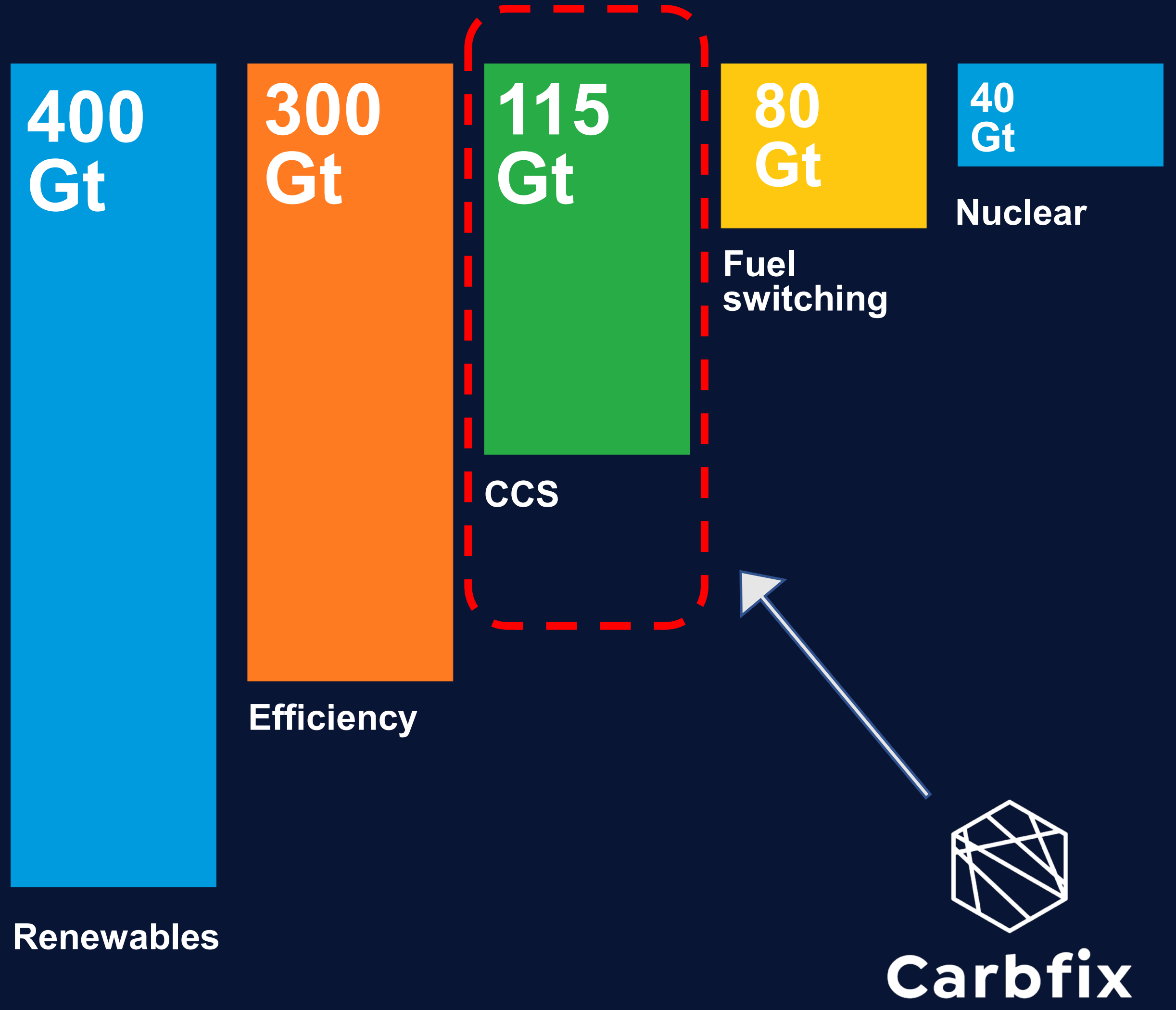
=

Solid carbonates (Calcite, magnesite and siderite)

$CaCO_{3\,(s)}$
$MgCO_{3\,(s)}$
$FeCO_{3\,(s)}$

Carbfix captures CO_2 and turns it into stone underground in under two years through proprietary technology that imitates and accelerates natural processes, providing a permanent and safe carbon storage solution.

Climate goals will not be met without carbon capture and storage.



Gigatons of avoided emission needed by 2060
International Energy Agency: Exploring Clean Energy pathways: The role of CO_2 storage 2019

From research to deployment

Carbfix project founded by OR, UI, Columbia and CNRS

Mineral storage confirmed

On-site capture and storage

Direct air capture and storage

Injection of seawater dissolved CO_2

DEMO UP CARMA

Preparation and design

Pilot phase

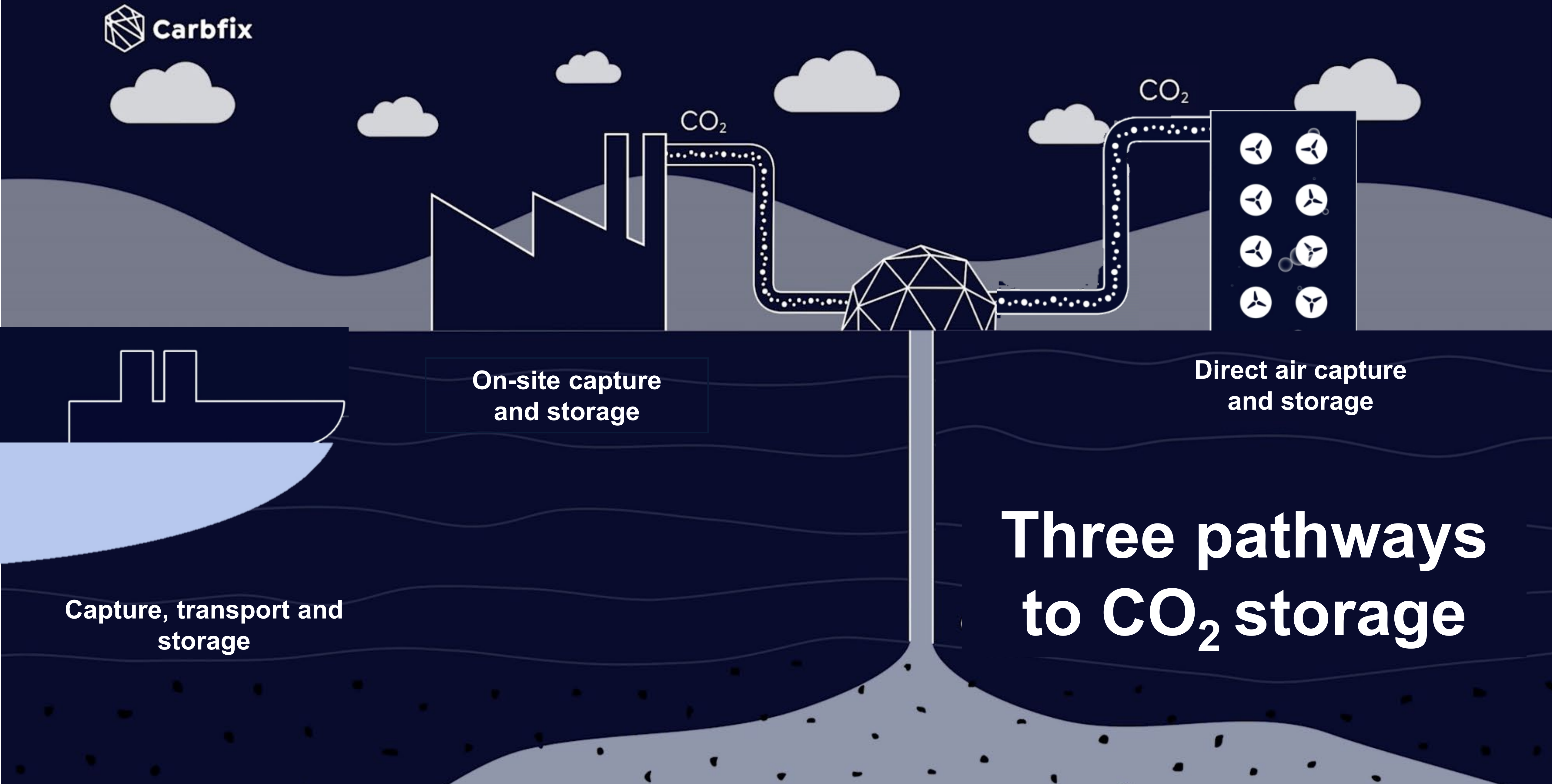
Industrial scale CCS

DAC and mineral storage

Scale-up

2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

Without safe and permanent storage, the carbon capture technologies will only solve one part of the problem



Three pathways to CO$_2$ storage

On-site capture and storage

Direct air capture and storage

Capture, transport and storage

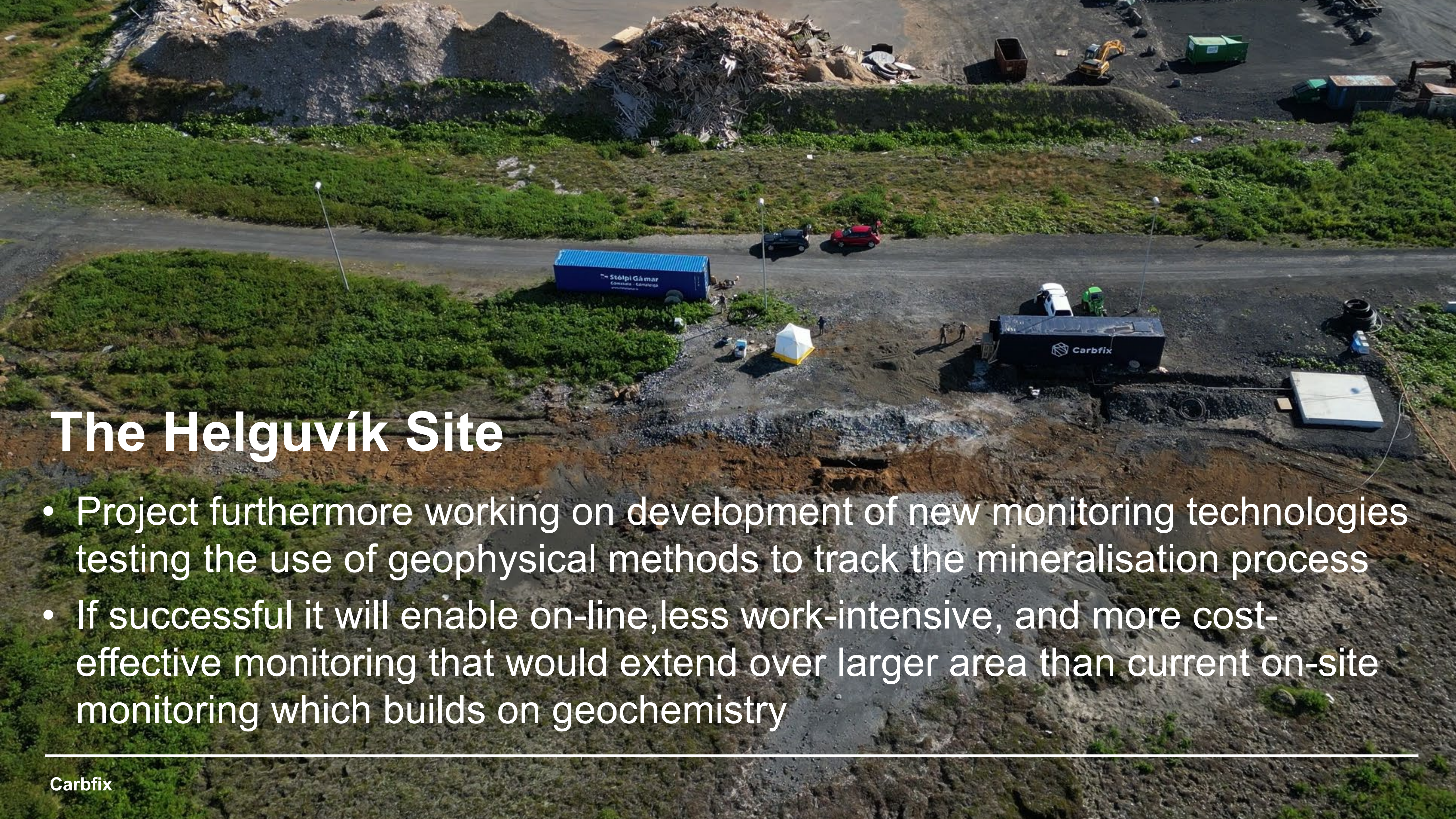
Injection of seawater dissolved CO_2 in Helguvík

2022-08-10

First CO2 transport arrived in Iceland

The first container with 20 tons of CO_2 from Switzerland now reached Iceland. In Iceland, a total of 1'000 tons are going to be injected into a geological reservoir with the aim of generating negative emissions. DemoUpCARMA aims to identify and investigate all aspects that are decisive for the feasibility and scalability of establishing such a CO_2 transport chain.

- First cross-boarder transport of CO_2 from Switzerland to Iceland in the fall of 2022
- World‘s first injection of seawater-dissolved CO_2 commissioned in the fall of 2023 using new portable injection system to inject CO_2 transported from Switzerland to Iceland
- Building on results from experimental work conducted in 2017-2020 demonstrating the of using seawater when injecting CO_2 into basalts



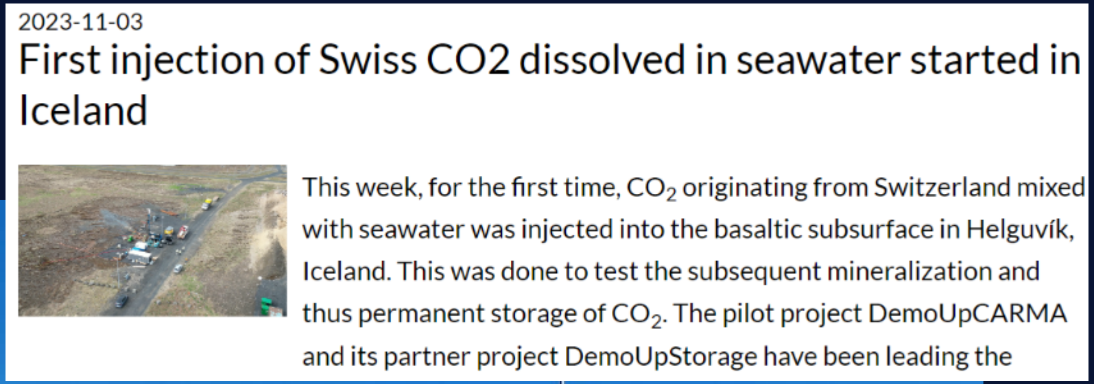
The Helguvík Site

- Project furthermore working on development of new monitoring technologies testing the use of geophysical methods to track the mineralisation process
- If successful it will enable on-line,less work-intensive, and more cost-effective monitoring that would extend over larger area than current on-site monitoring which builds on geochemistry

The Helguvík Site

Seastone – seawater dissolved CO_2 for injection

- If successful, this approach extends the applicability of injection of dissolved CO_2
- Coastal areas, water scarce areas, and the vast offshore basalts unlocking storage potential on Gt scale
- Paves the road for projects such as the Coda Terminal, for large scale import of CO_2 for permanent storage
- Important milestone for countries such as Switzerland to achieve climate goals



2023-11-03

First injection of Swiss CO2 dissolved in seawater started in Iceland

This week, for the first time, CO_2 originating from Switzerland mixed with seawater was injected into the basaltic subsurface in Helguvík, Iceland. This was done to test the subsequent mineralization and thus permanent storage of CO_2. The pilot project DemoUpCARMA and its partner project DemoUpStorage have been leading the

Voigt et al., GCA, 2021; Marieni et al., IJGGC, 2021

Carbfix

Thank you
for your attention

Monitoring of CO_2 injection and storage in the underground

Stefan Wiemer for the
DemoUpStorage Team

Final DemoUpCarma Meeting

Zürich, 6 Dezember 2023

DemoUpCARMA is funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN)

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

Federal Office for the Environment FOEN

So we brought our CO_2 to Icleand....

And we mix it with seawater and injected it at the Helguvík Site - Thanks Carbfix!

ETH zürich

eawag aquatic research

EPFL

UNIVERSITÉ DE GENÈVE

That was the easy part …

..the hard part is to find it again!

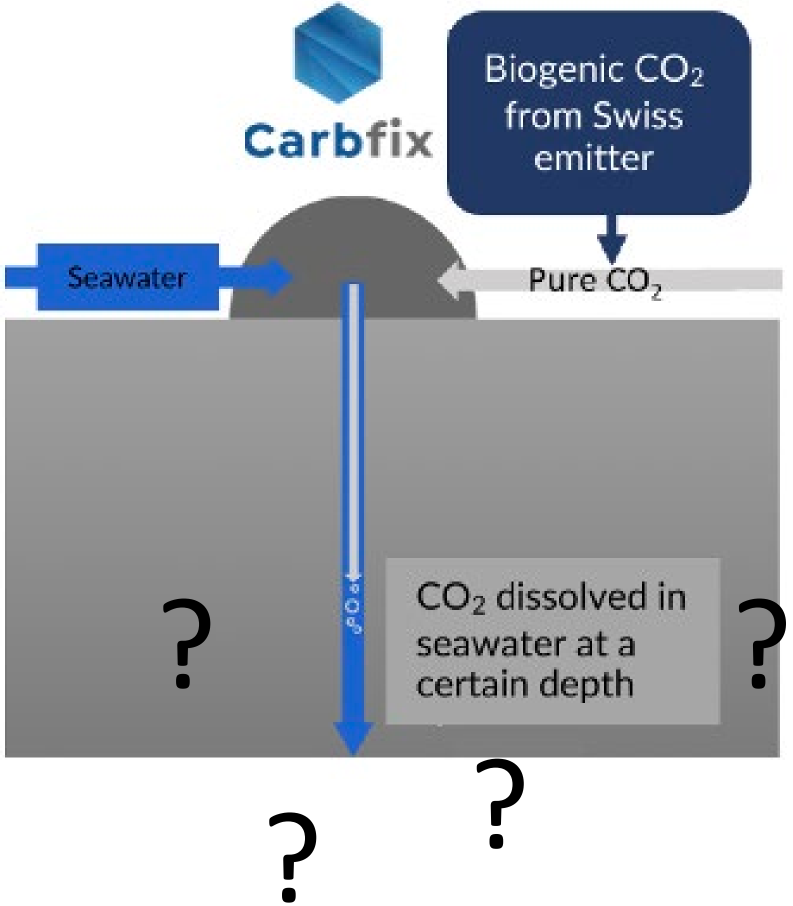
DEMO UP STORAGE

We send a couple of Swiss experts ...
but they could not find it.

So we sent our own experts ...
meet Katinka and Jonas!

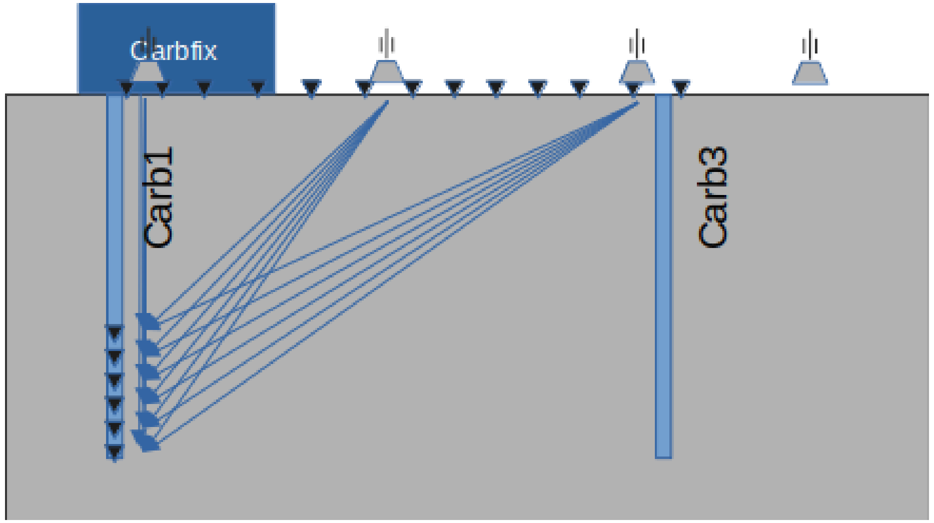
To answer these questions

- Is the Swiss CO_2 mineralizing in-situ, and with sea-water also?
- Or is it migrating onwards – into the ocean?
- Is there leakage/degassing taking place? Is there induced micro-seismicity?
- Can we track the processes with geophysical methods?
- And which techniques are best suited and most cost-effective?
- What can we learn about the Swiss situation from this?

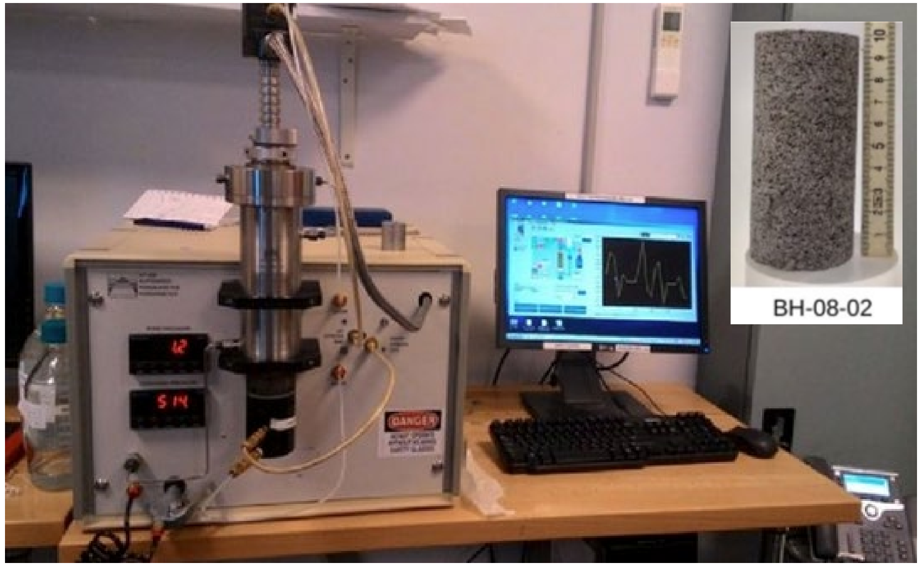


How to find CO_2 in the underground (and understand what happened to it)

1. Study it in the lab under controlled conditions, so that you know what to look for.
2. Trace it with a pump and gas-spectrometer.
3. Find the change in seismic velocities caused by filling pores with mineralized CO_2.
4. Find the changes in electrical resistivity cause by mineralization.
5. Model this all and see if you can match observations.

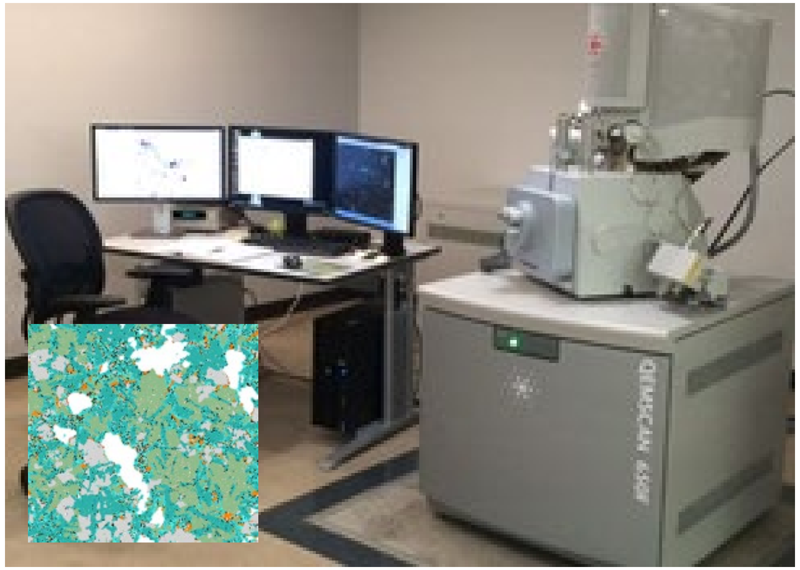


Analytical methods



Automated permeameter-porosimeter
Core Test AP-608

Density, 3D K, 3D Phi



Automated Quantitative Petrographic Analysis
QEMSCAN QUANTA 650 F

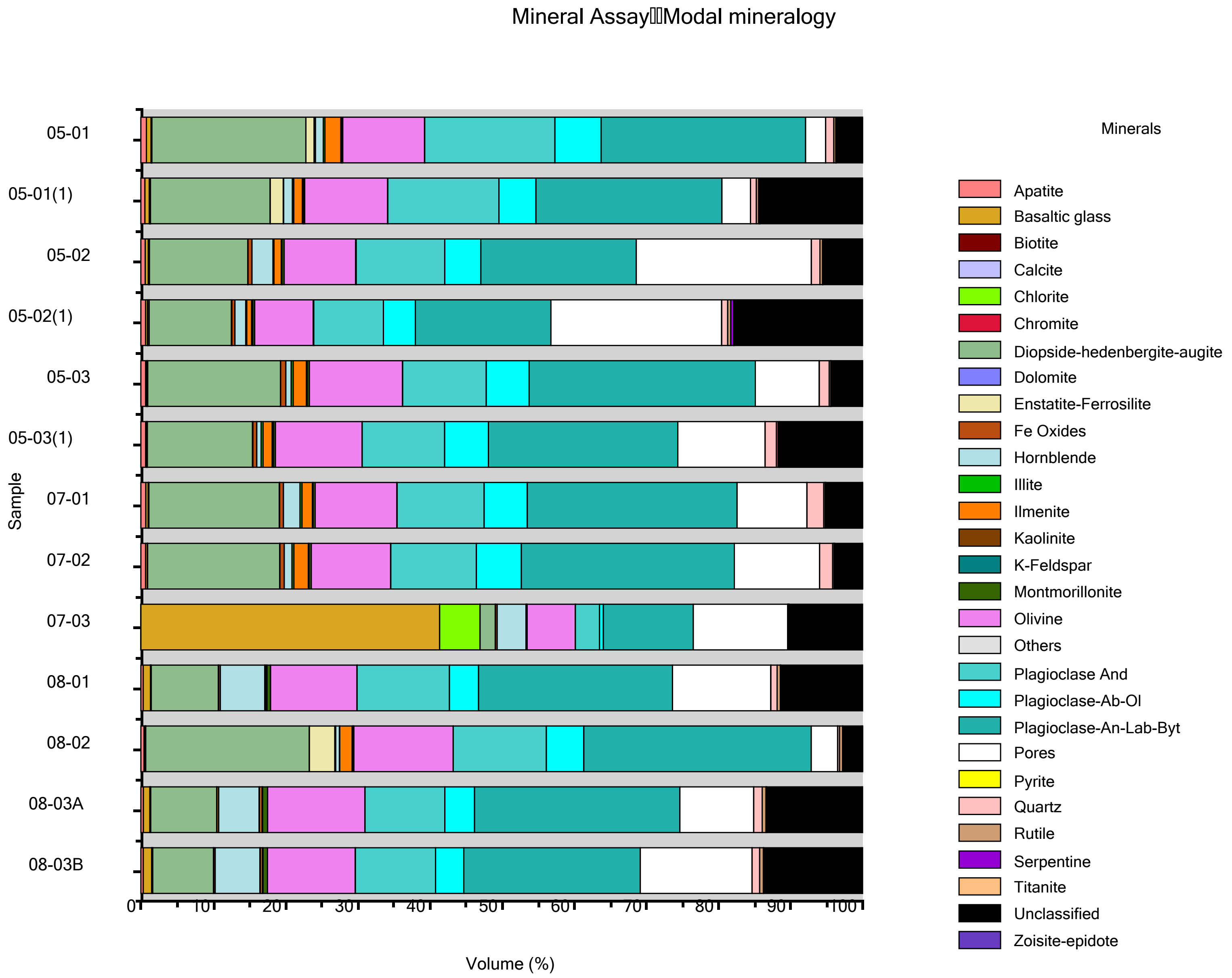
Texture, Mineralogy, Lithotype, 2D Phi

XRF spectrometry (geochemical analysis)
Panalytical Axios Max

Major, Minor and Trace chemical elements

- Basalt is not just Basalt.
- Chemistry is quite variable – and relevant

BH-08-02
(6.5 %)



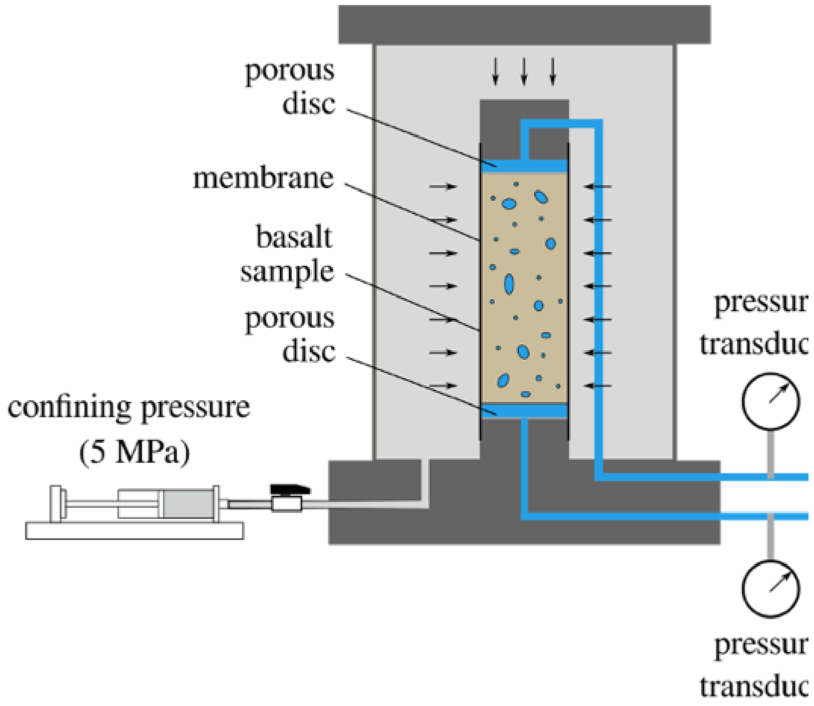
Exposing Basalts to CO_2 dissolved in sea-water in the lab for two months does the trick!

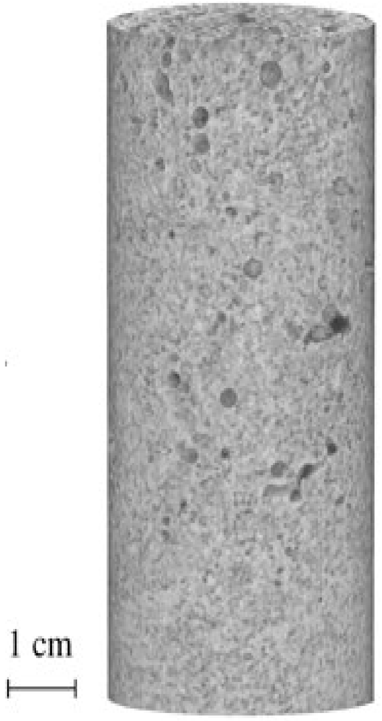
2 months CO_2 exposure

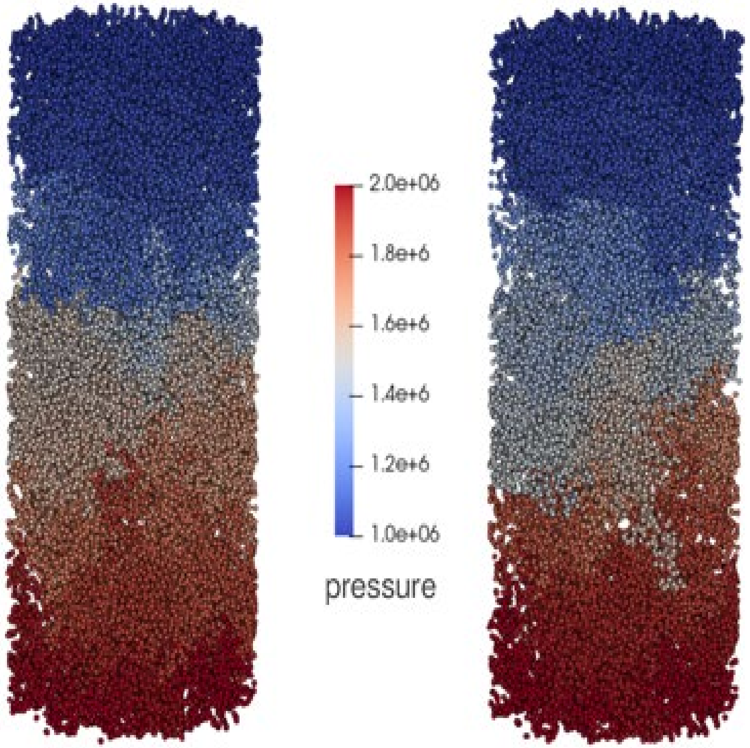
Porosity:
- X-rays: 8.9 %
- Lab: 13.5 %

Pre-CO_2:
k = $1.67 \cdot 10^{-16}$ m^2

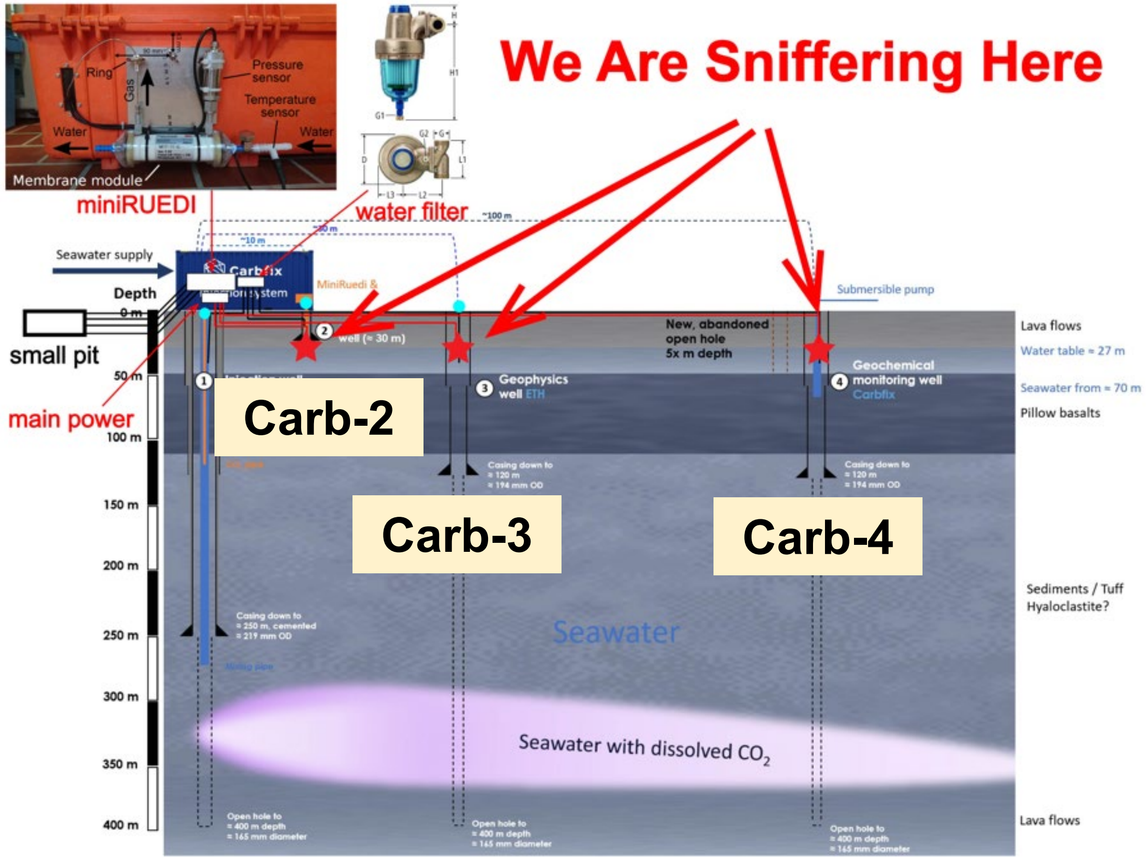
Post-CO_2:
k = $6.90 \cdot 10^{-17}$ m^2

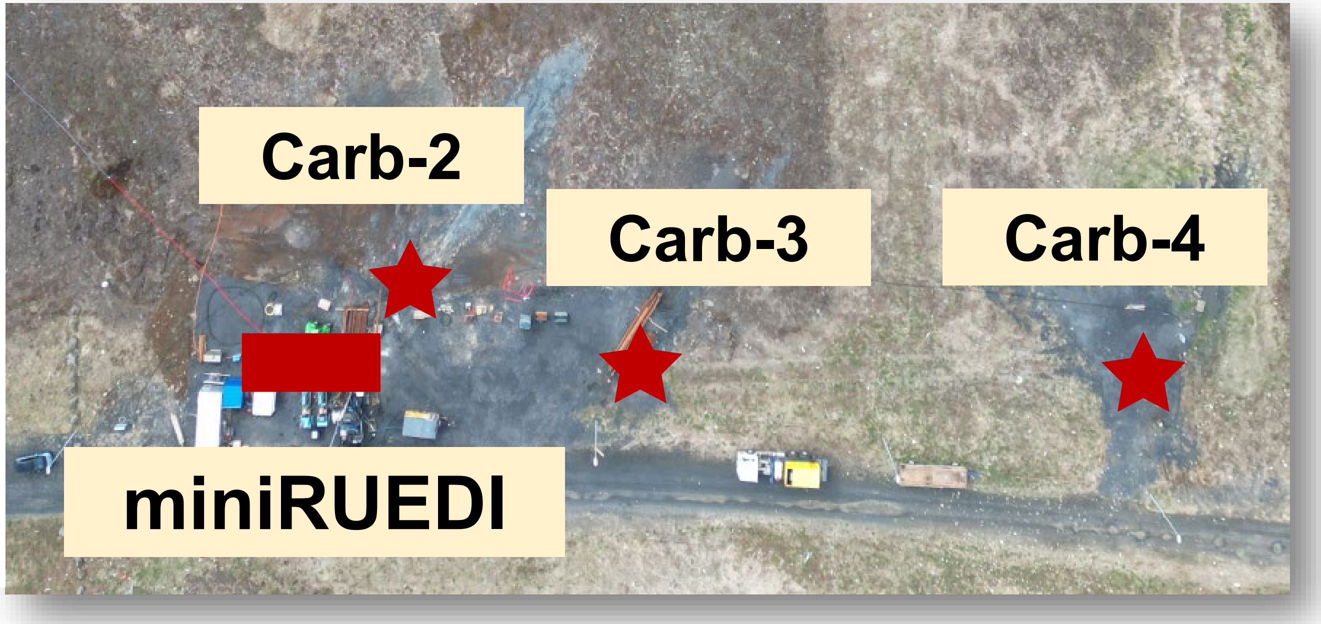






Dissolved Gas Monitoring





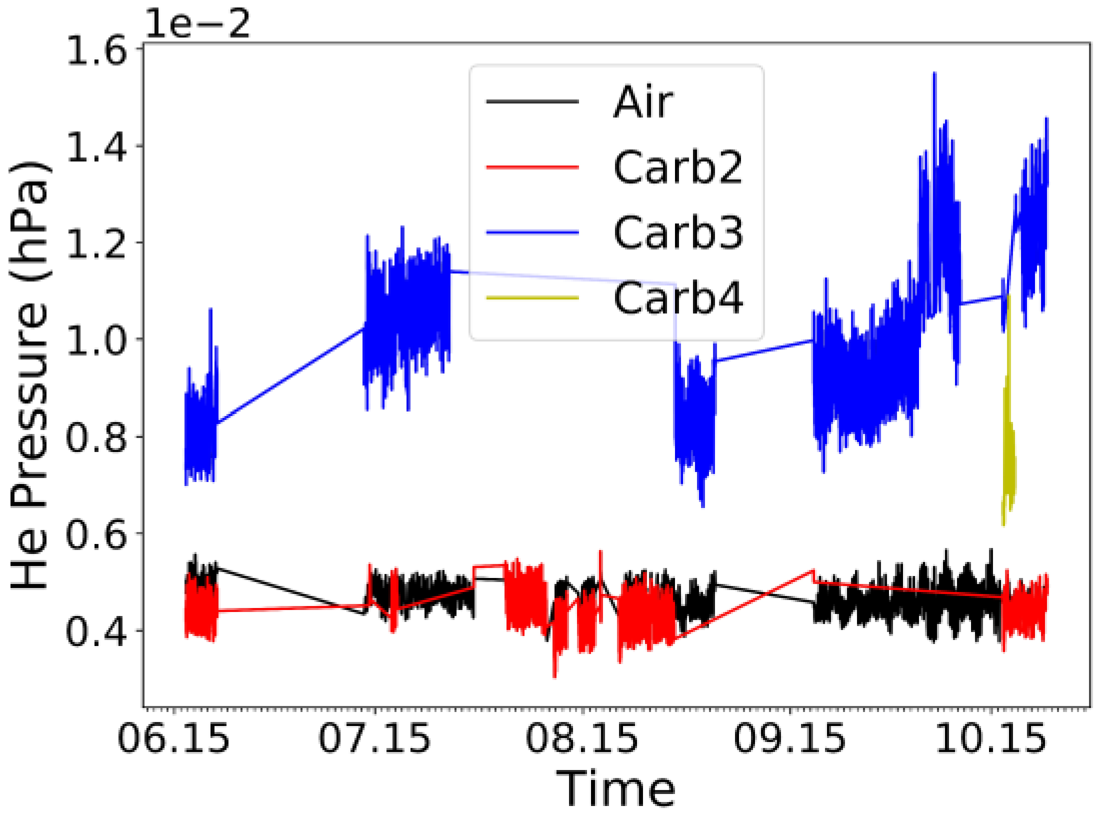
The miniRUEDI is sniffing dissolved gases in Carb-2, Carb-3 and Carb-4 wells

DEMO UP STORAGE

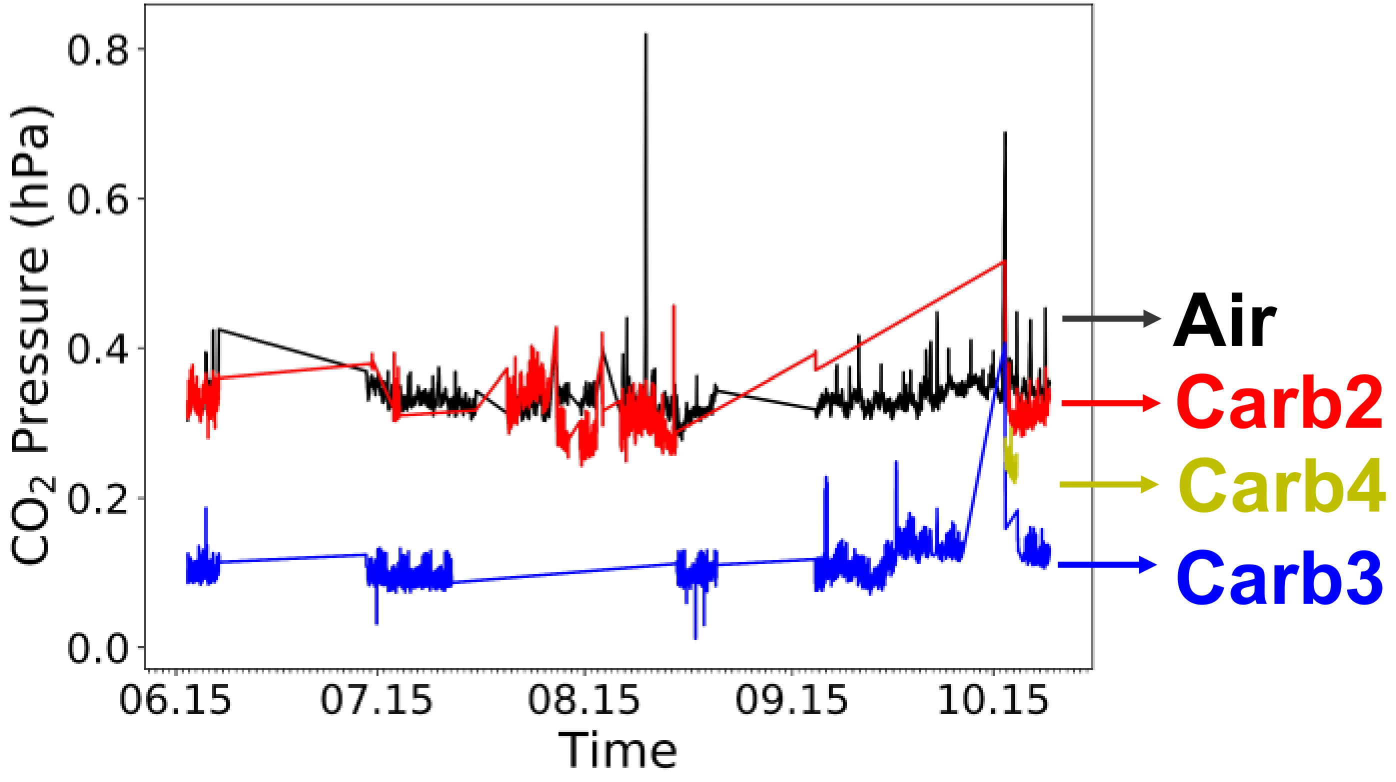
eawag
aquatic research

Dissolved Gas Time series

Helium time series

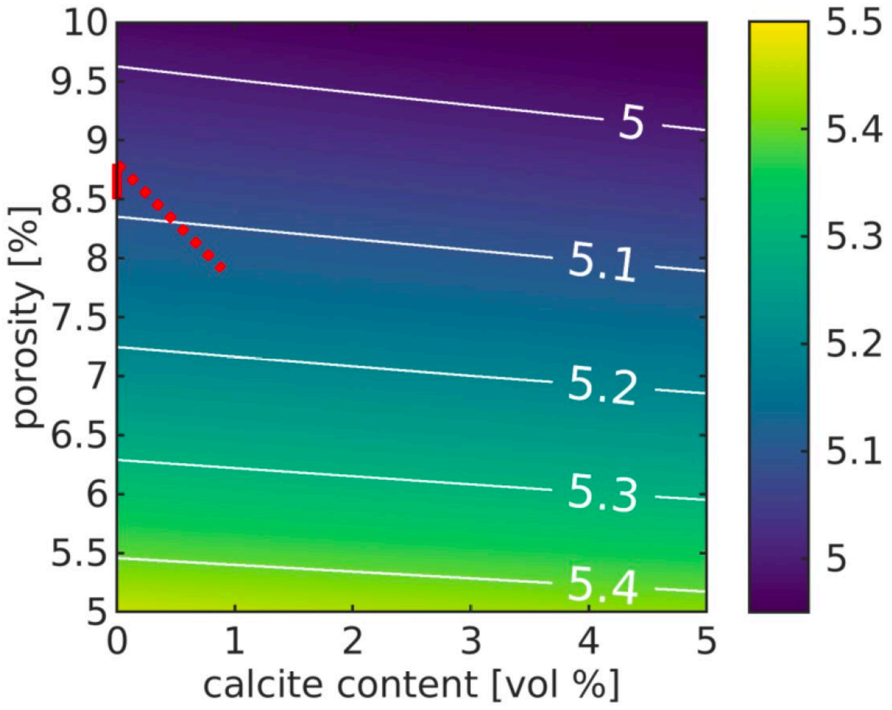


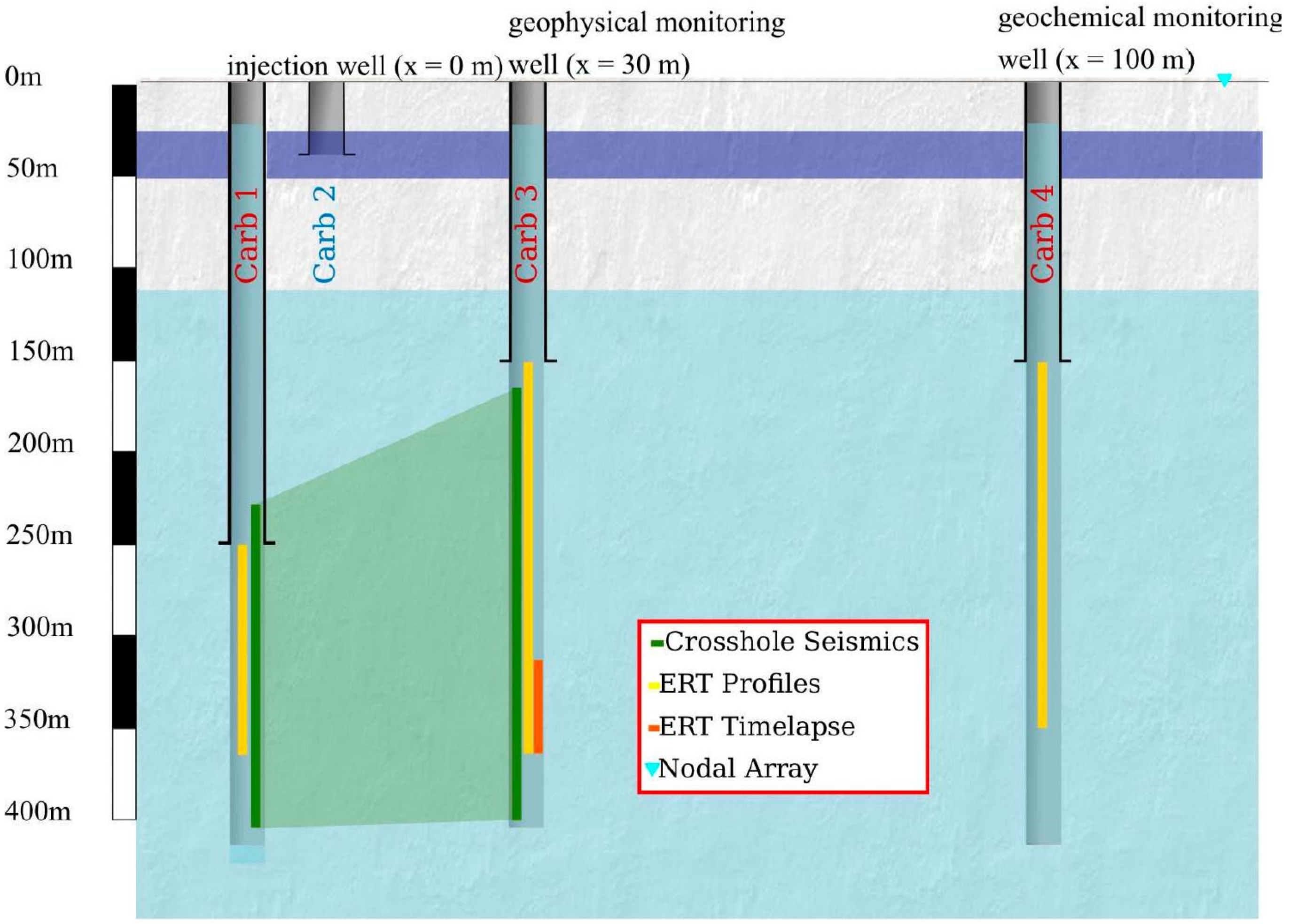
CO_2 time series



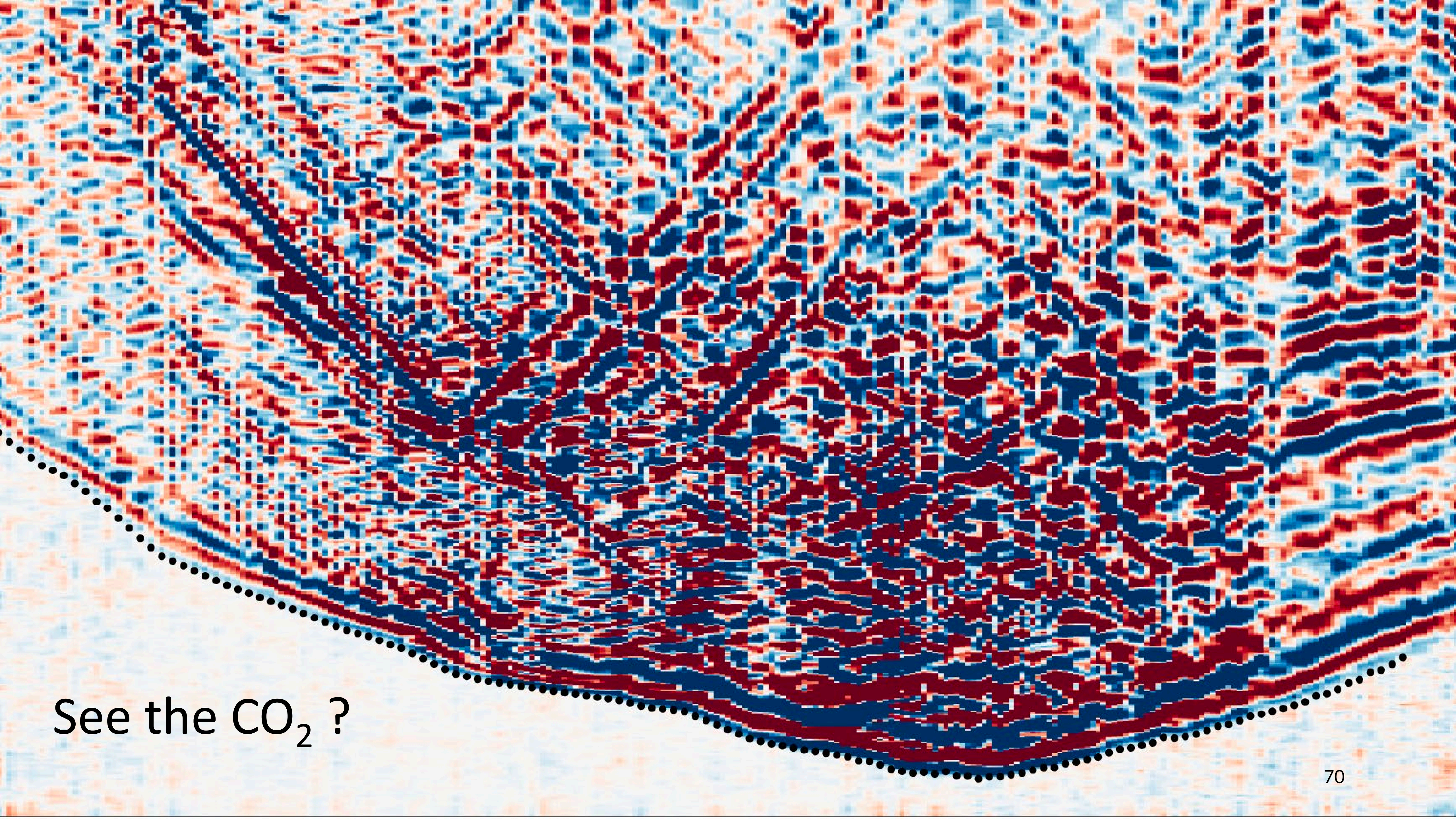
Baselines of the three wells

Mineralization changes seismic velocities





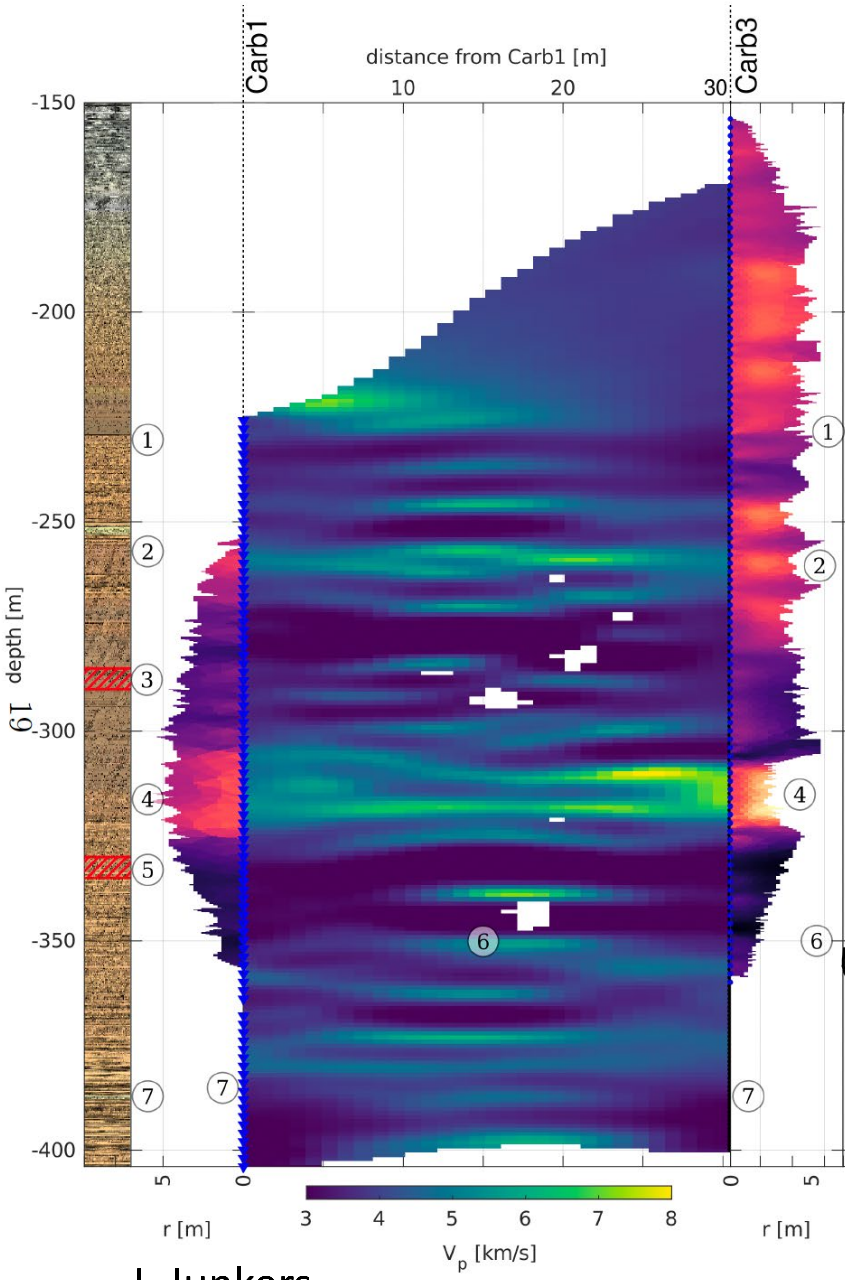
Real world impressions



See the CO_2 ?

OK ... we only just started ... Sorry.

- The baseline measurements are done and are promising.
- The CO_2 injection (just) started (with 12 months delay ... Earth science can be complicated in times of wars).
- Seismic images look promising – now we need to repeat the measurements in 6 – 12 month and subtract the two images: Differential change in velocity (we should see 1%)
- The miniRuedi should see the CO2 – and the tracer Helium (every 15 minutes)
- The daily resistivity measurements should see the CO_2 and mineralization.



J. Junkers

Hang in there... just 6 more months...

While we wait.... let´s turn to Switzerland.

Geological storage of CO_2 has many advantages

Economical

- Long transport is expensive
- CCS in Switzerland encourages investments
- ‘Offshore’ storage is generally more expensive than ‘onshore’

Ecological

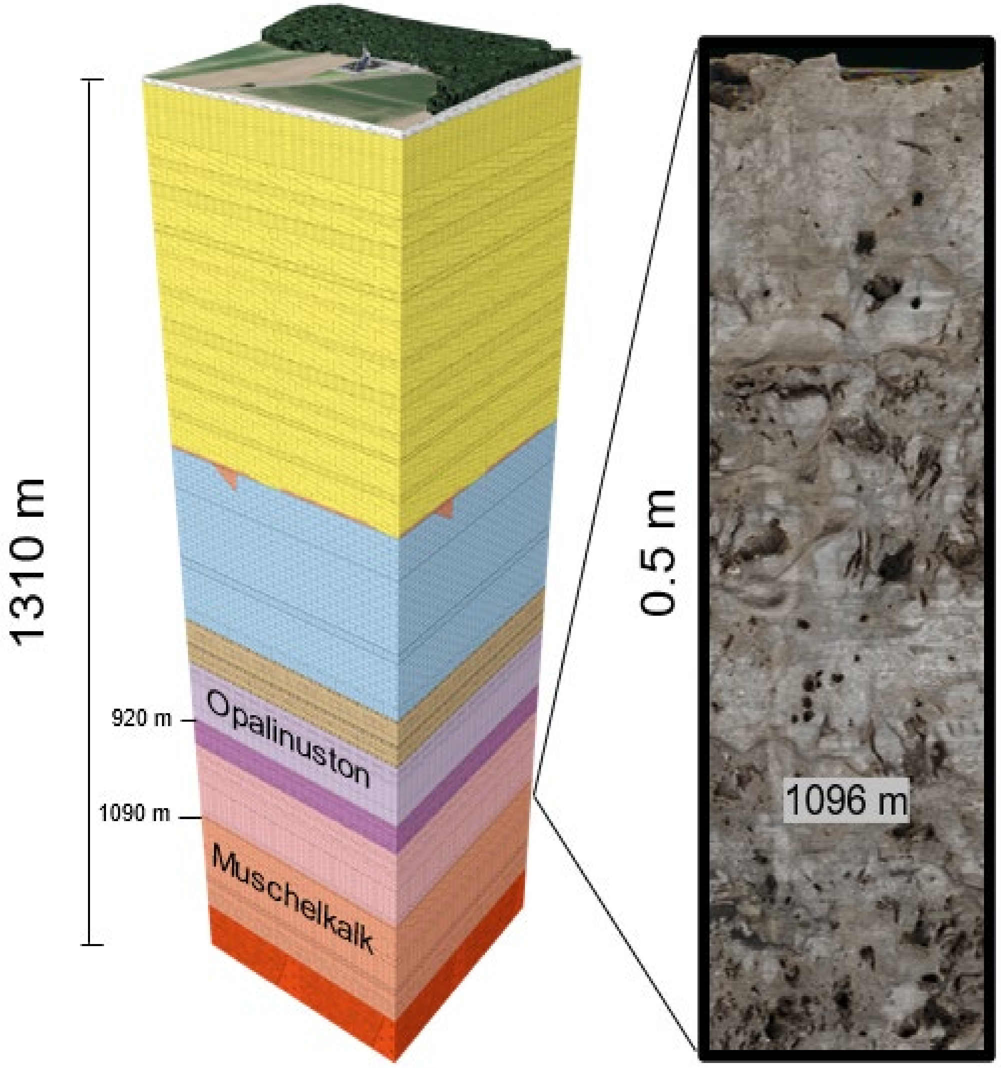
- Long transport causes additional CO_2 emissions

Socially

- Swiss citizens favour solutions that take care of our own "waste"

Self-sufficient

- Independence from foreign storage facilities and international supply chains



L. Diamond

BUT: Is it geologically possible, safe and socially acceptable?

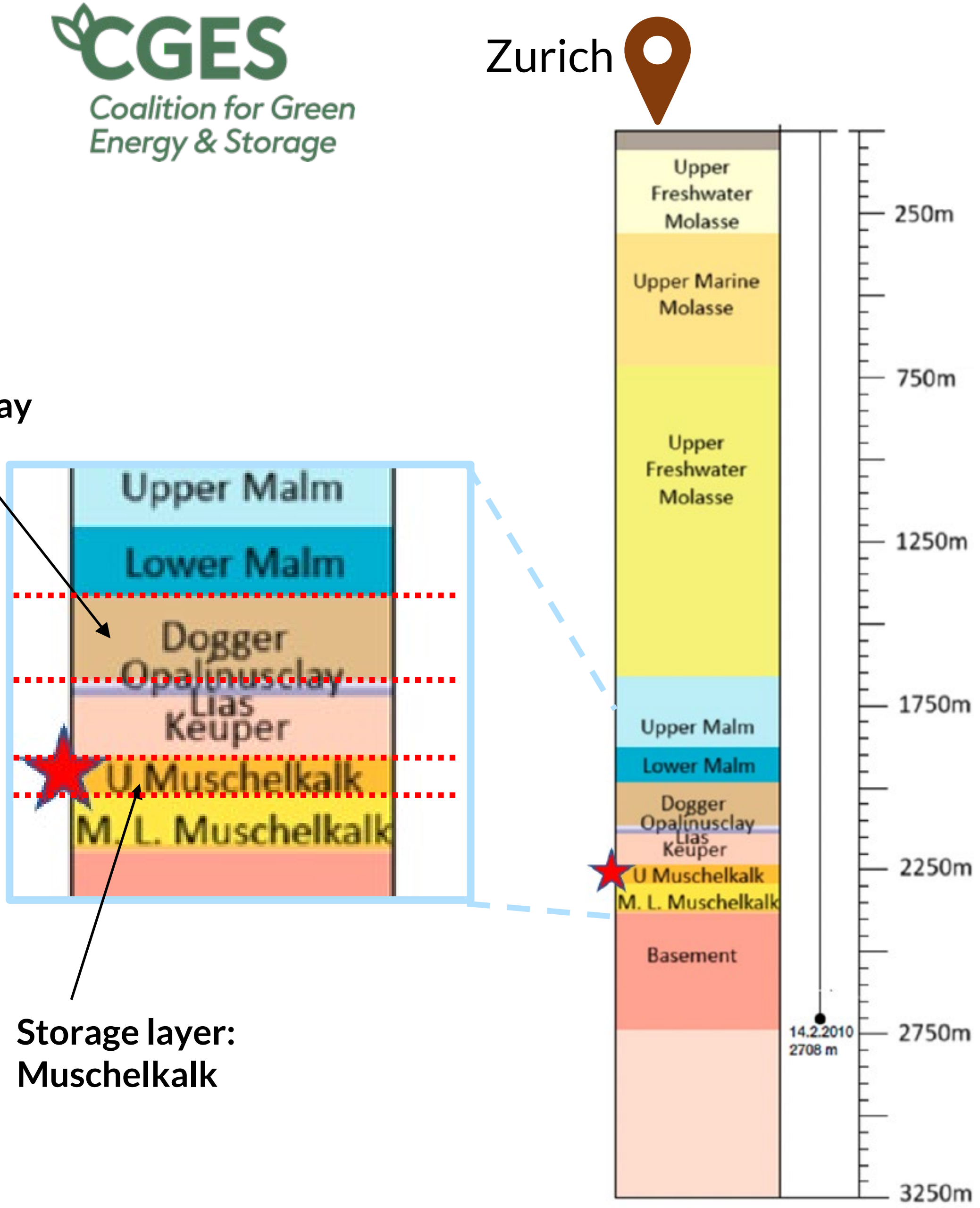
- We don't know for sure at the moment
- ‘Offshore’ is not an option for Switzerland
- There are good cover layers in Switzerland
- Switzerland's reservoir rocks are less thick, less porous and less permeable than elsewhere in the world

→ How big is the storage potential?

→ Are storage projects in Switzerland socially accepted?

→ We should find out!

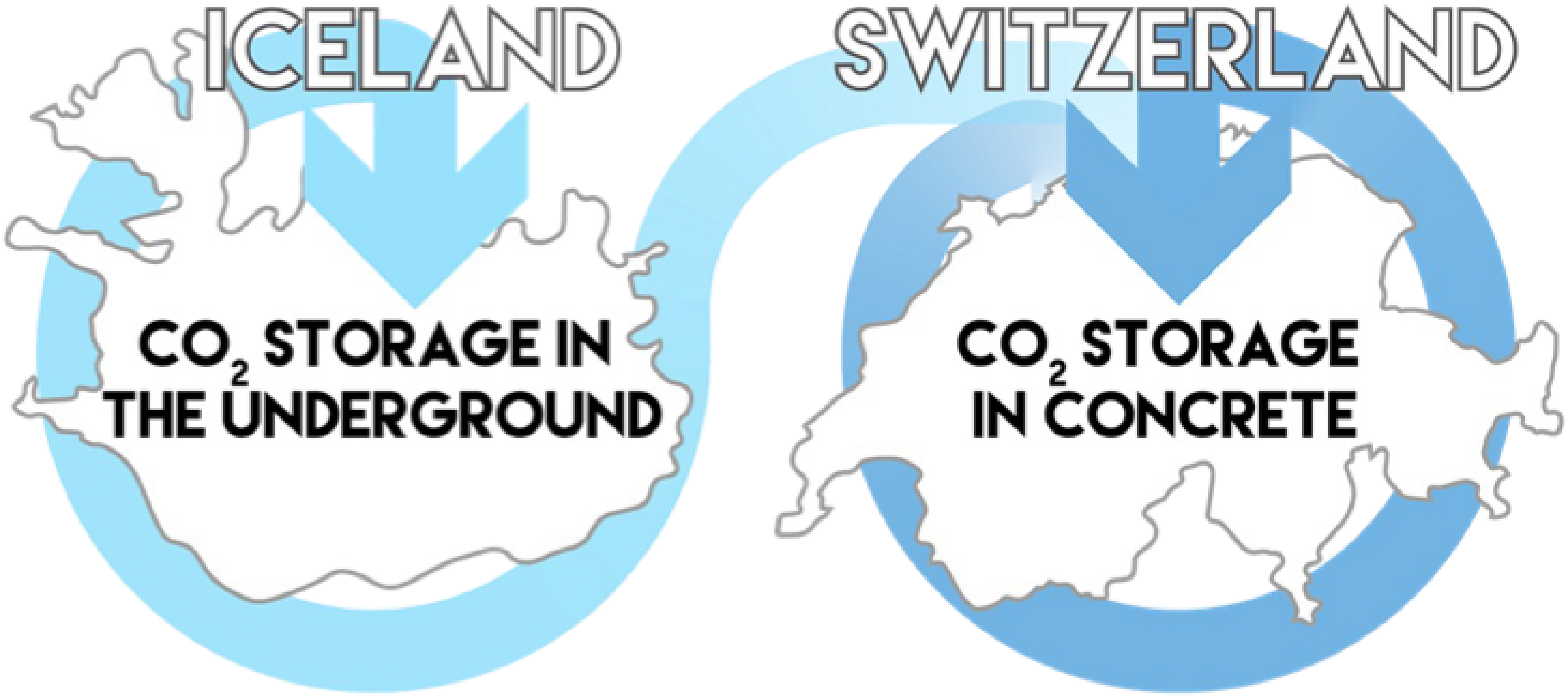
→ The findings from DemoUpCarma are helpful.



Top layer: Opalinusclay

Storage layer: Muschelkalk

Danke!


ICELAND
SWITZERLAND
CO_2 STORAGE IN THE UNDERGROUND
CO_2 STORAGE IN CONCRETE

Systemic aspects

Life cycle assessment and system analysis of CO_2 capture, transport, and storage (CCTS) technologies

Julian Nöhl, Johannes Burger, Pauline Oeuvray, Paolo Gabrielli, Jan Seiler, David Shu, Viola Becattini, Marco Mazzotti, André Bardow

ETH Zurich

DemoUpCARMA is funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN)

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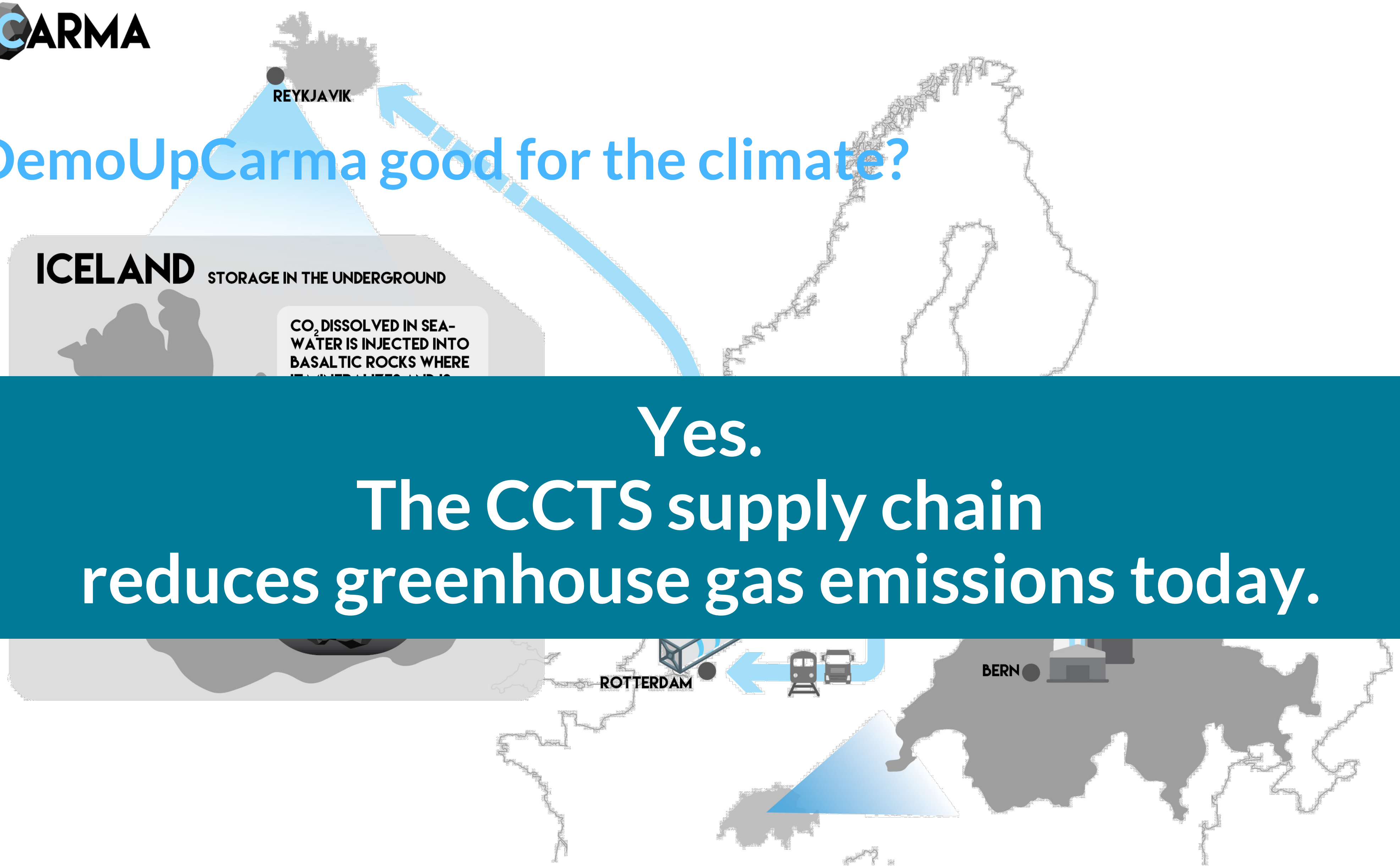
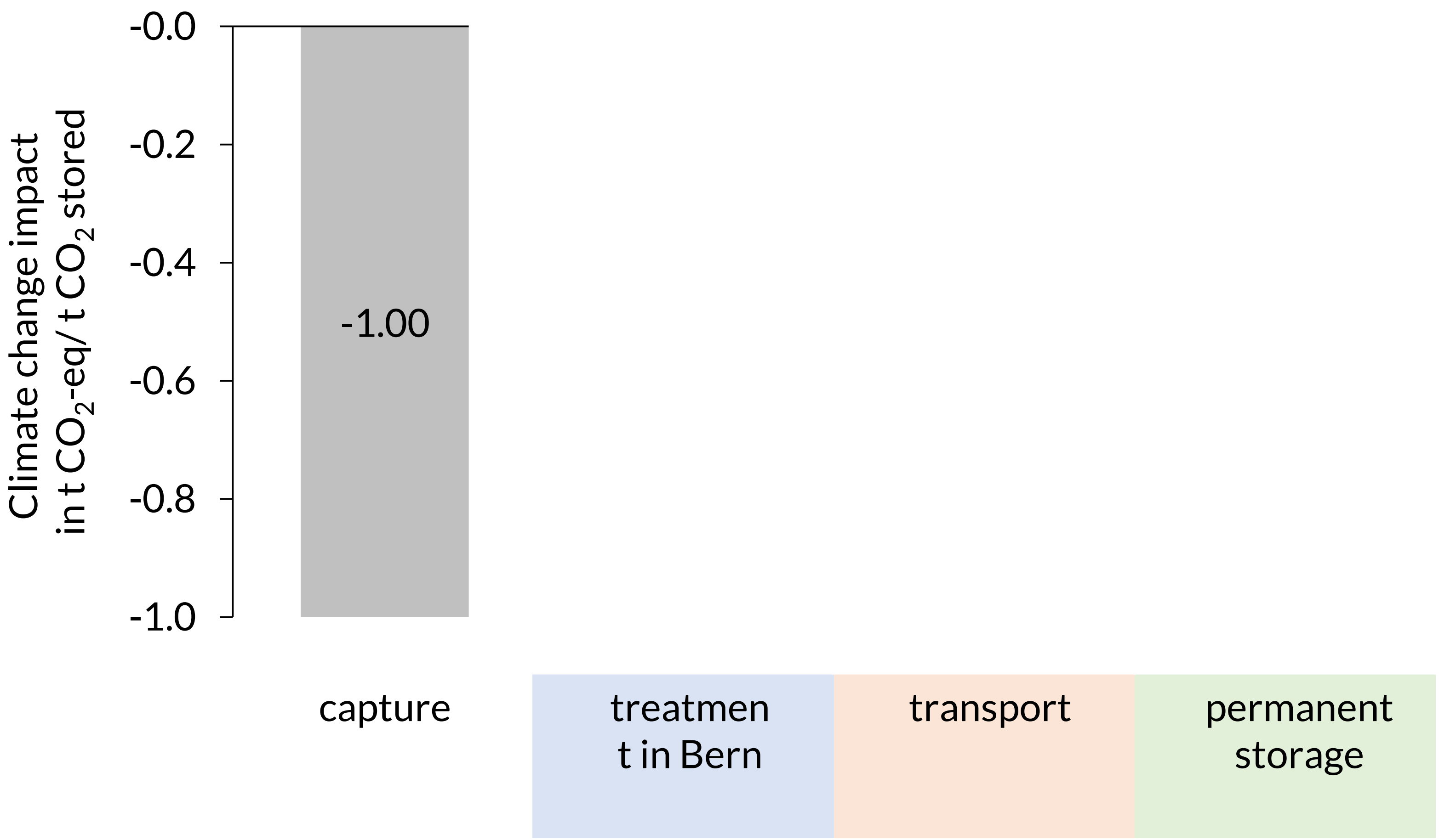
Is DemoUpCarma good for the climate?



Yes.
The CCTS supply chain reduces greenhouse gas emissions today.

The CCTS supply chain reduces greenhouse gas emissions today



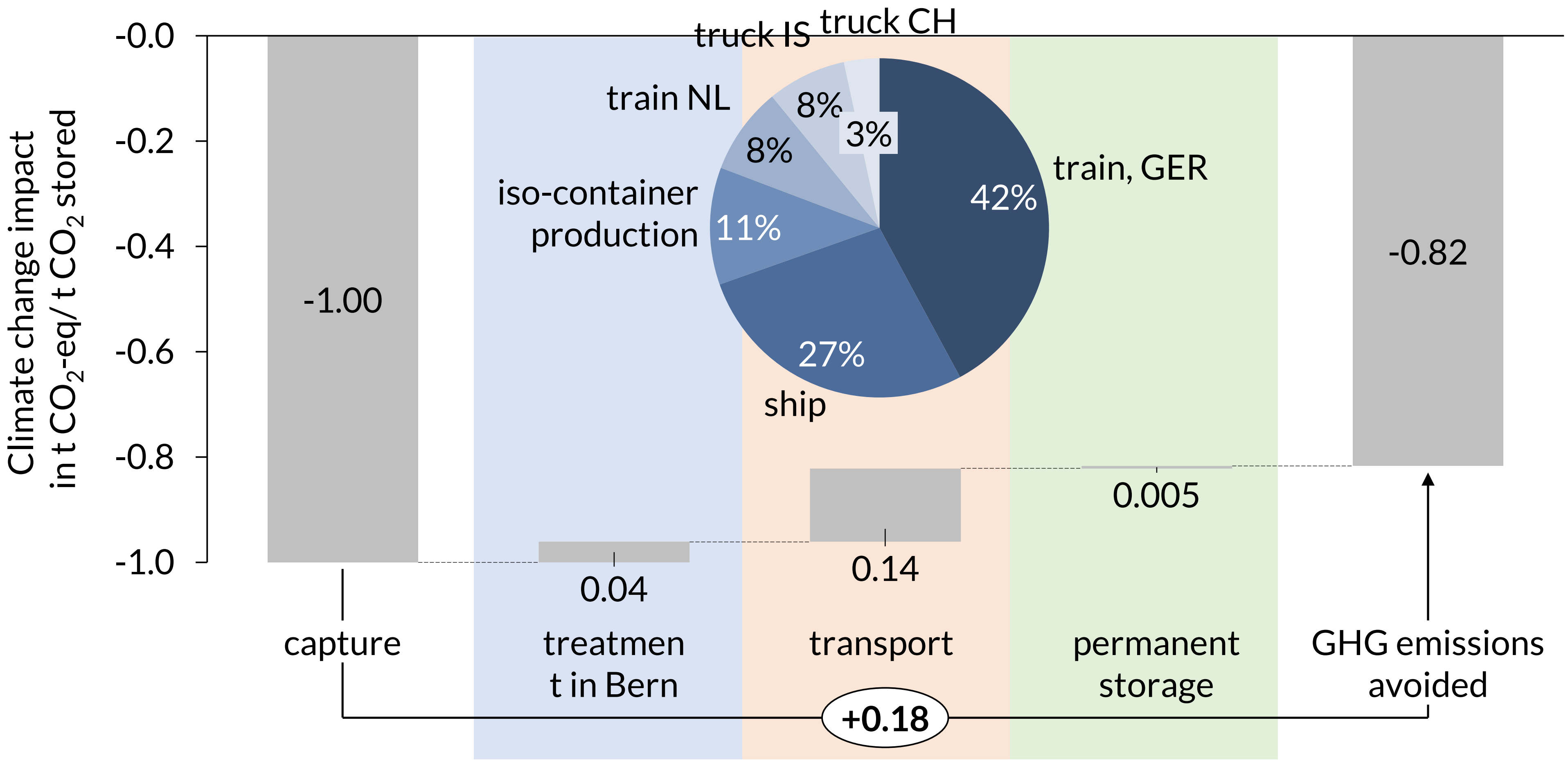
Johannes
Burger

Julian
Nöhl

Jan
Seiler

David
Shu

The CCTS supply chain reduces greenhouse gas emissions today



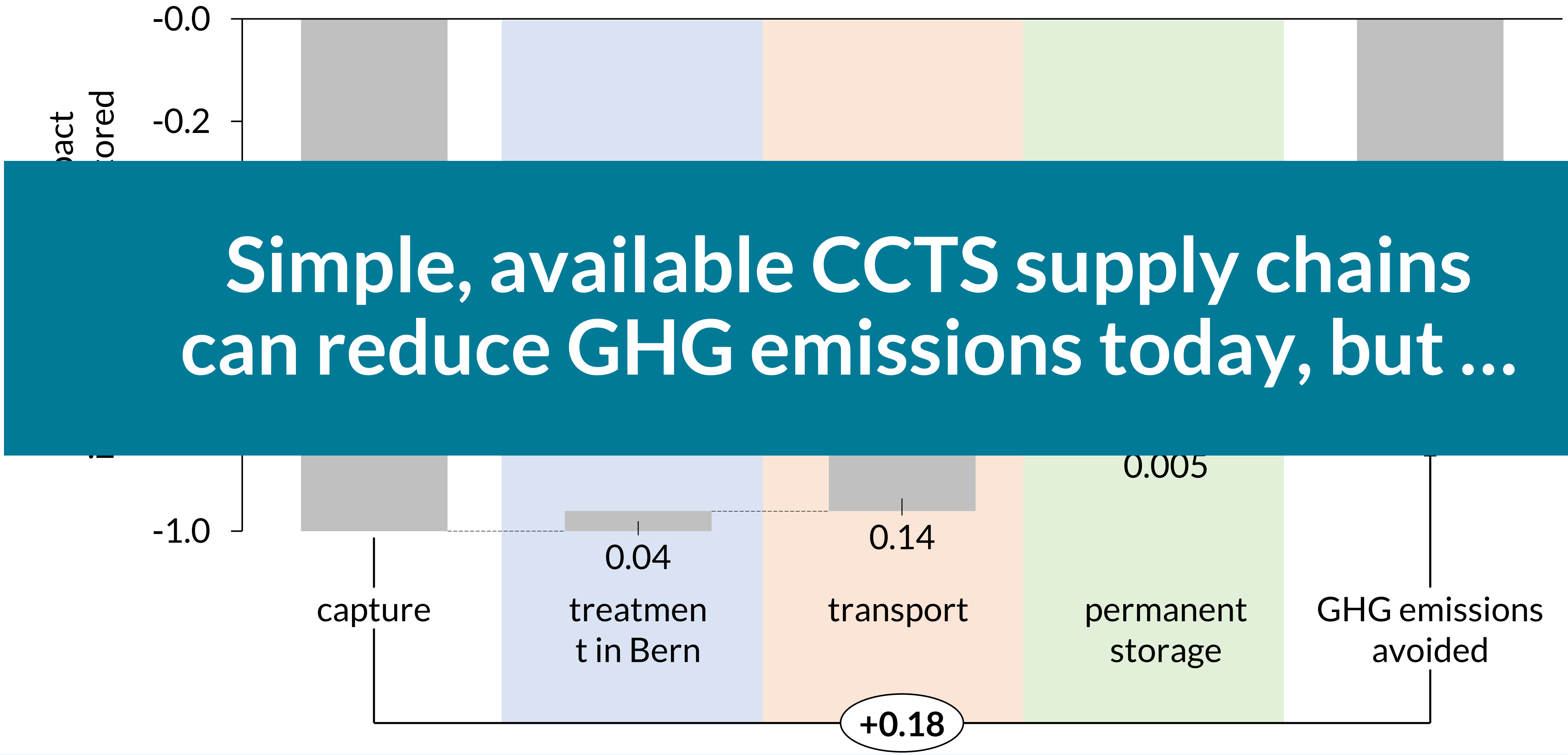
Johannes Burger

Julian Nöhl

Jan Seiler

David Shu

The CCTS supply chain reduces greenhouse gas emissions today



Simple, available CCTS supply chains can reduce GHG emissions today, but …

Johannes Burger

Julian Nöhl

Jan Seiler

David Shu

DEMO UP CARMA

Reducing climate impacts = Increasing other environmental impacts

ment

climate change (I)
ozone depletion (I)
acidification (II)
eutrophication freshwater (II)

Transport and electricity dominate other impacts

h

human health effects, non-cancer (III)

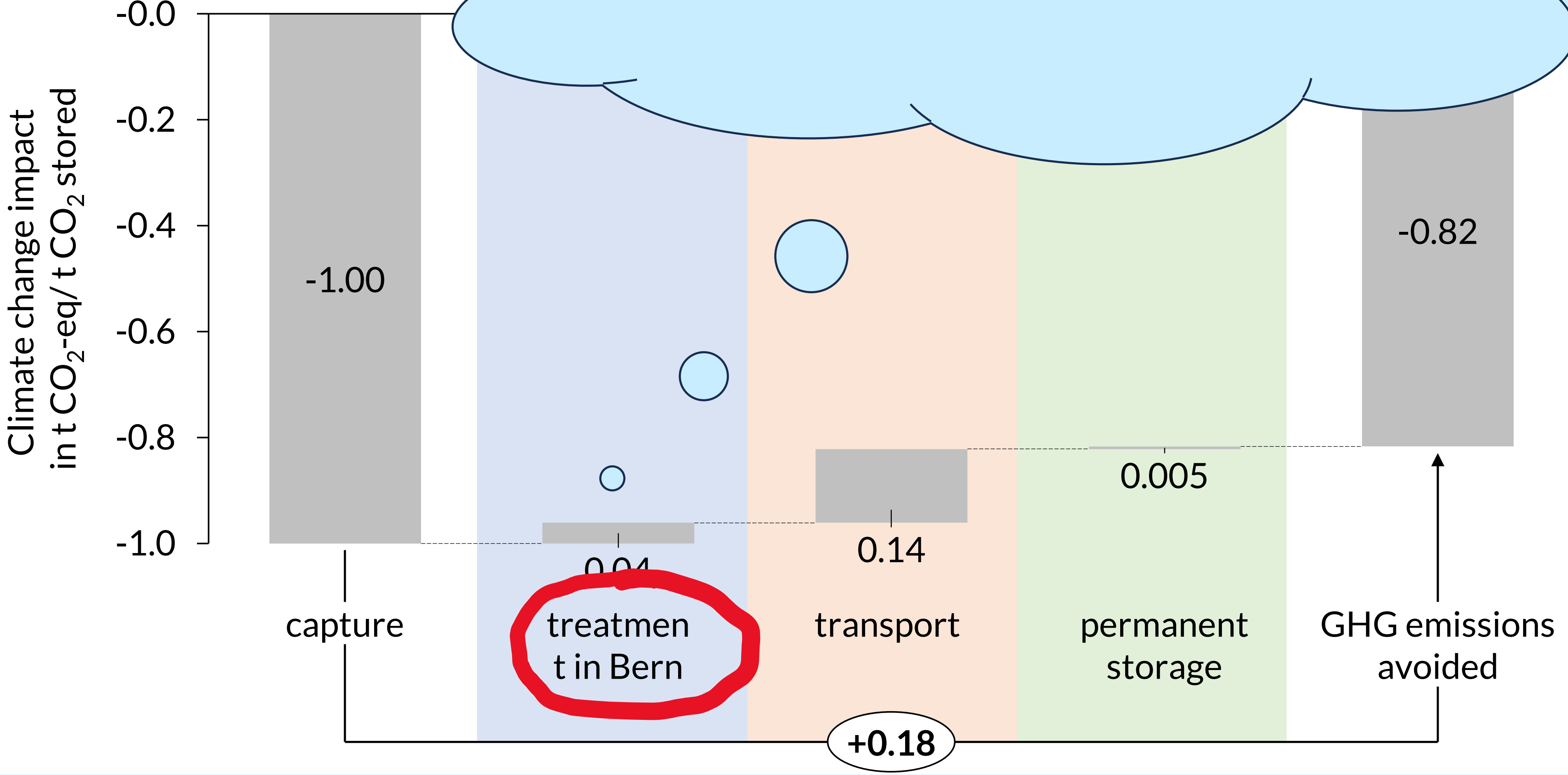
resources

resource use, energy carriers (III)
resource use, minerals and metals (III)
land use (III)
water use (III)

Quality levels: recommended and (I) satisfactory; (II): in need of improvement; (III): use with caution

The CCTS supply

How transferable and scalable ?



Johannes Burger

Julian Nöhl

Jan Seiler

David Shu

Designing large-scale CCTS value chains

Hagenholz
Waste-to-Energy plant
ERZ

Kehrichtverwertungsanlagen im Kanton Zürich, https://www.zh.ch/de/umwelt-tiere/abfall-rohstoffe/abfaelle/abfallanlagen/kehrichtverwertungsanlagen.html

The Zürich Waste-to-Energy plant

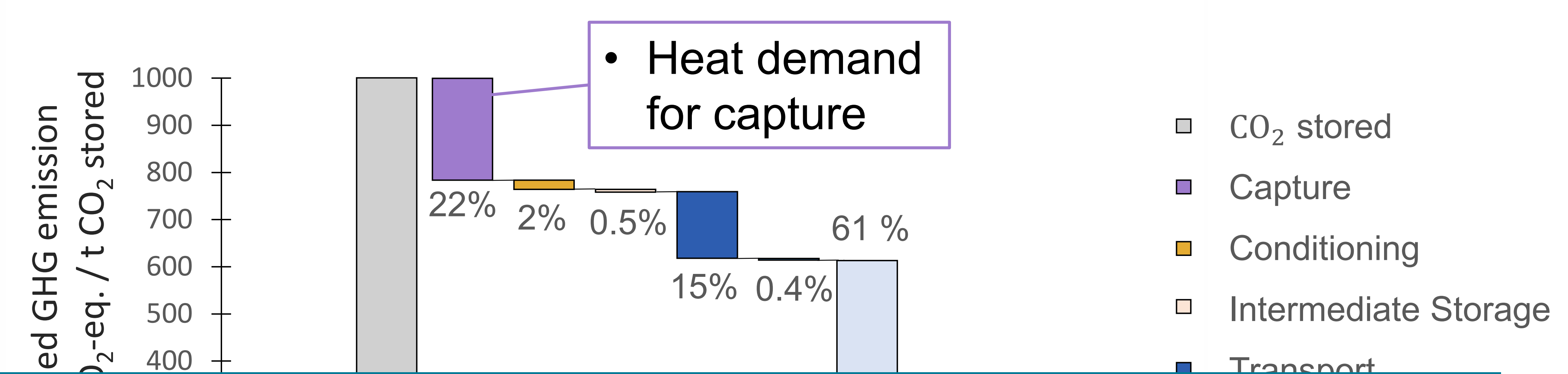
Three services:

1. waste management,
2. district heating supply
3. electricity supply

Emissions:
400 ktCO_2/y from 2027 (50% biogenic)

→ 4. Service: CO_2 reduction and removal

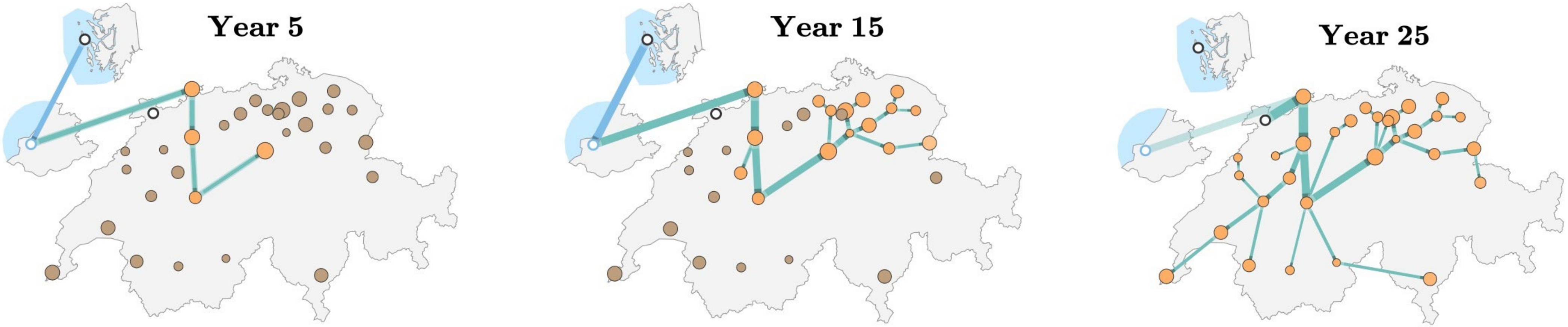
Avoiding GHG emissions with early-mover chains?



- Heat demand for capture

Early-mover CCTS chains can reduce GHG emissions today.

From early-movers towards large-scale deployment



We can plan the transition from early-movers to cost- and climate-efficient resilient CCTS chains


Pauline Oeuvray


Johannes Burger


Viola Becattini


Paolo Gabrielli

Becattini, Gabrielli et al., *Int. J. Greenh. Gas Control 117* (2022)

Summary

Early-mover CCTS chains
can reduce GHG emissions today.

Environmental trade-offs are unavoidable
- but are reduced by better technologies
and cleaner transport, electricity and heat.

We can plan the transition from early-movers
to cost- and climate-efficient resilient CCTS chains.

Energy Week @ ETH 2023

CO_2 capture integration in waste-to-energy plants: Case study for the city of Zurich

ETH Zürich, Switzerland
6th December, 2023

Tuvshinjargal Otgonbayar, ETH Zurich, t.otgonbayar@ipe.mavt.ethz.ch

DemoUpCARMA is funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN)

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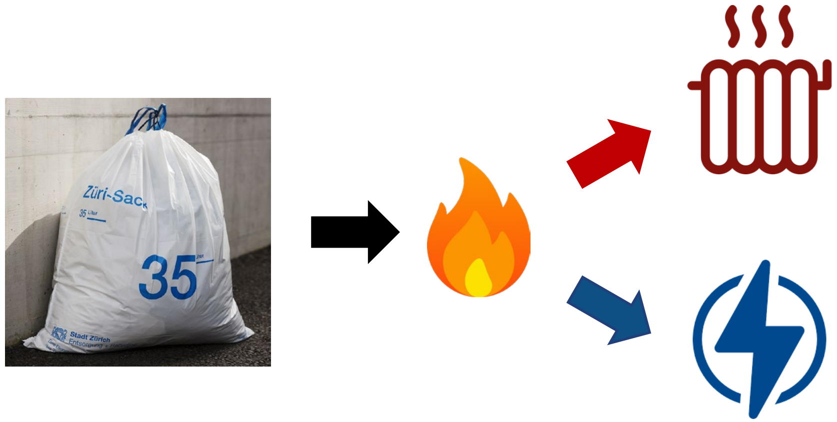
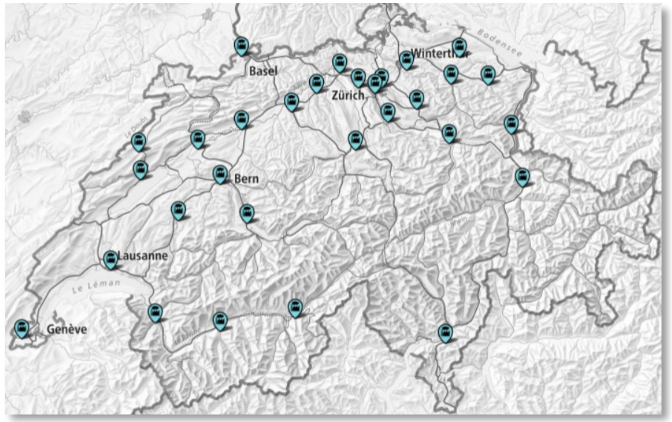
Introduction

- Waste-to-energy (WtE) plants incinerate municipal solid waste (MSW) that cannot be recycled to supply
  - heat to customers such as industry or the district heating (DH) network
  - electricity to the power grid
- 29 WtE plants in Switzerland → 4.5 million tonnes CO_2 per year
- Hard-to-abate emissions
- 50% of the CO_2 is considered biogenic (wood vs. plastic)
- Carbon capture and storage (CCS) can lead to negative emissions
- Heat and electricity for CCS can be provided by WtE plant
- District heating is considered a vital demand

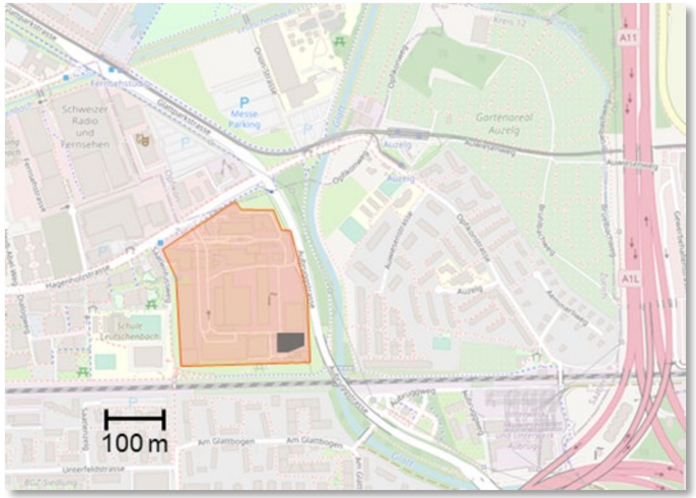




To what extent is such an integration energetically feasible?

CO_2 capture integration for KVA Hagenholz

- WtE plant in Zurich – KVA Hagenholz
  - Burns 250’000 tonnes of MSW every year
  - Emits roughly the same amount of CO_2
- Located in a densely populated area with a large district heating network
- Provides every year to the city of Zurich:
  - District heating to 80’000 households
  - Electricity to 10’000 households
- Lots of waste heat generated in summer due to lower demand
- Expansion of a third incineration line in 2027
  - Projected CO_2 emissions: 400’000 tonnes of CO_2 every year
  - Largest prospective WtE plant in Switzerland
  - Plans for carbon capture and storage
- Energy requirements? Space requirements?



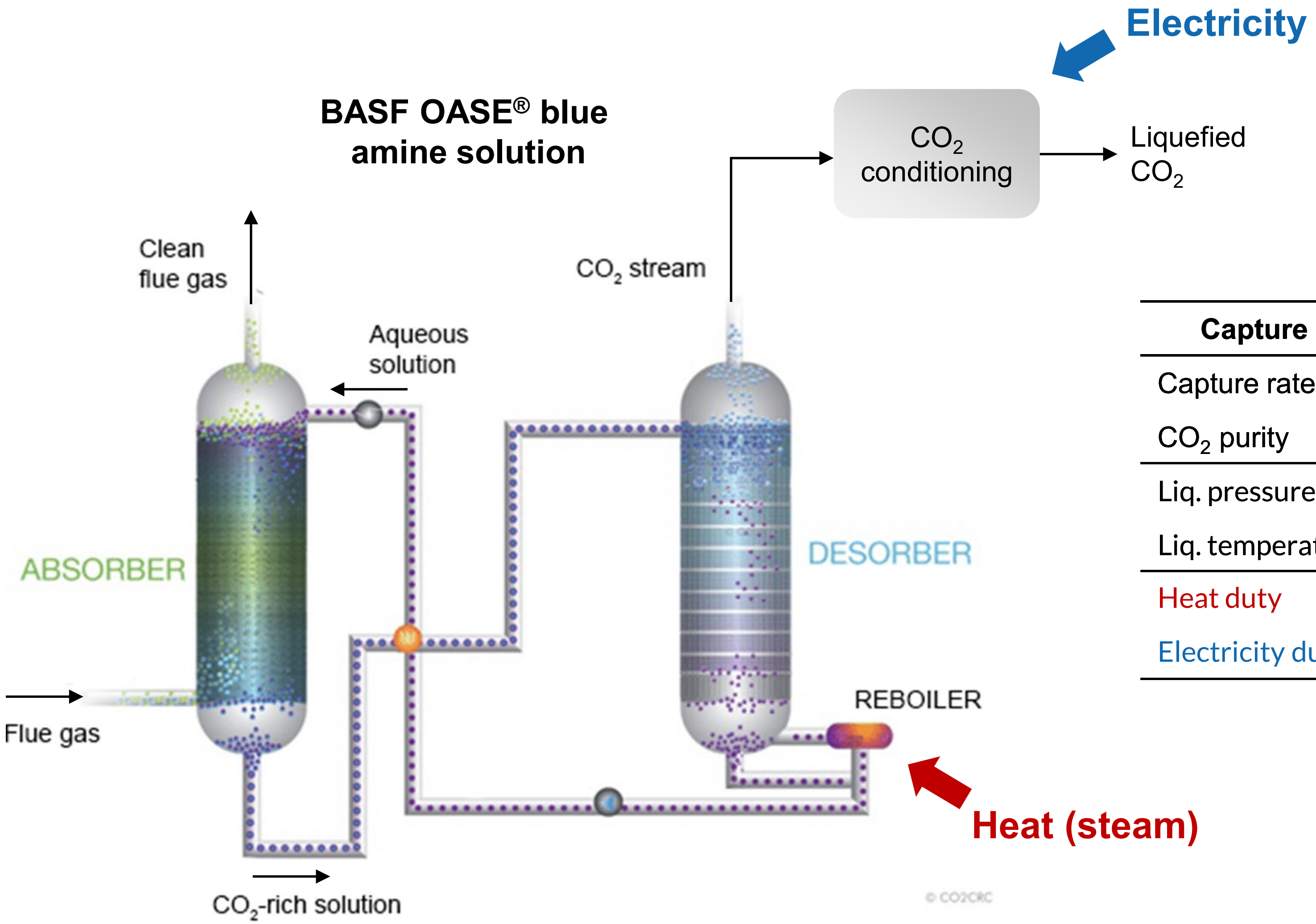
Entsorgung + Recycling - Stadt Zürich, 2022

Amine-based post-combustion capture process

INTRODUCTION | KVA HAGENHOLZ | **CO_2 CAPTURE** | RESULTS | CONCLUSION

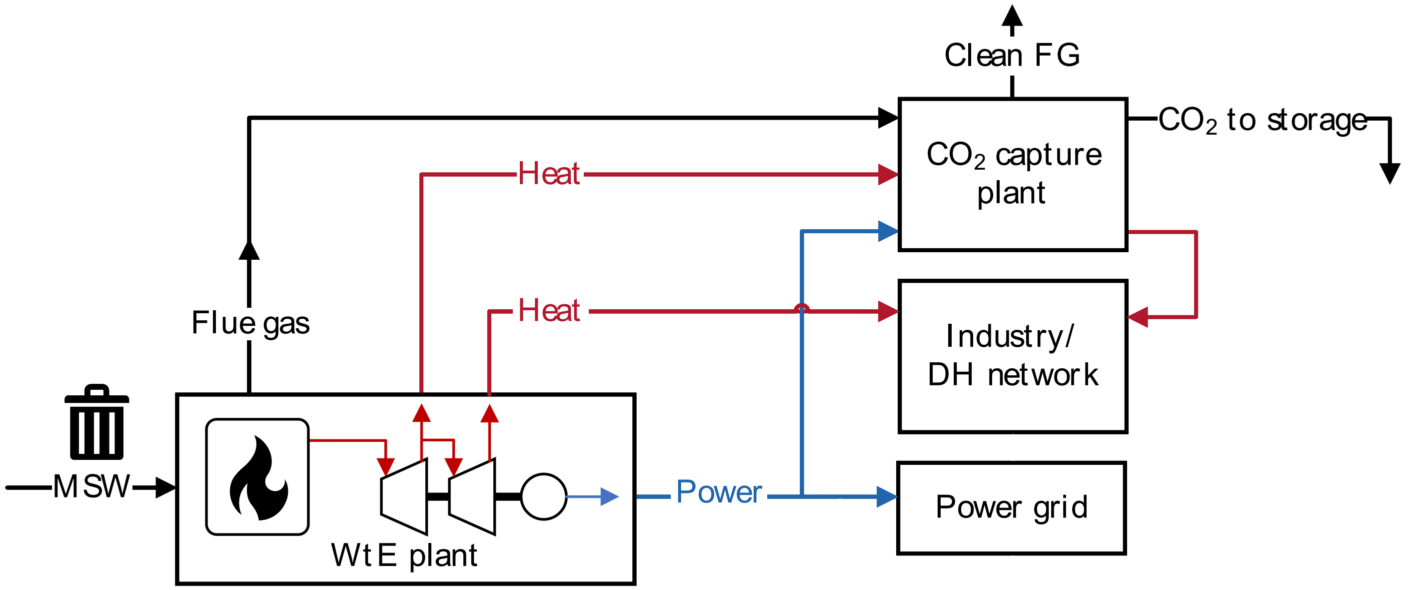
Flue gas conditions	
CO_2 flow rate	400 kt/yr
CO_2 concentration	12%
Temperature	40 °C
Pressure	1 atm

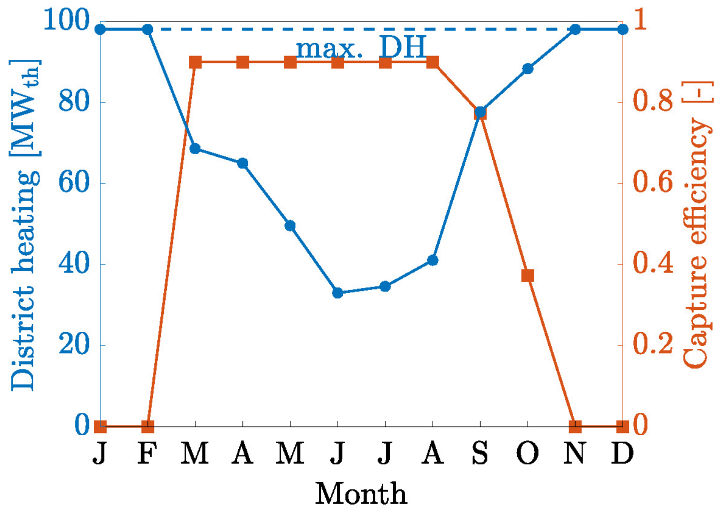
BASF OASE® blue amine solution

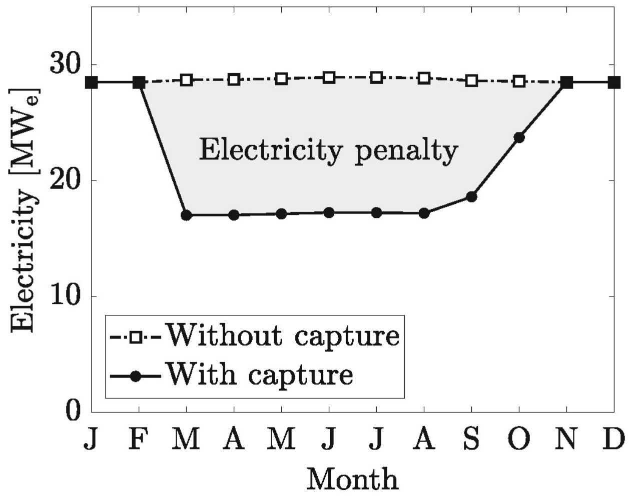


Capture specifications	
Capture rate	90%
CO_2 purity	> 99.9%
Liq. pressure	23 bar
Liq. temperature	-37 °C
Heat duty	35 MW_{th}
Electricity duty	9 MW_e

Results - seasonal CO_2 capture





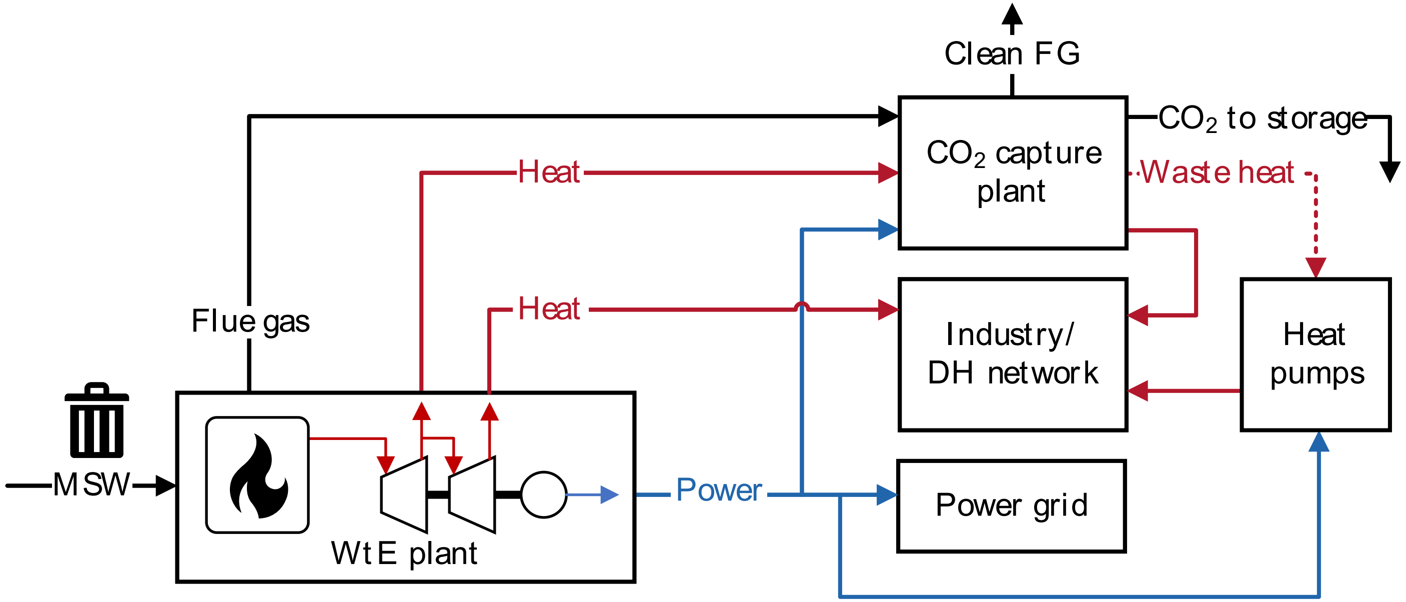


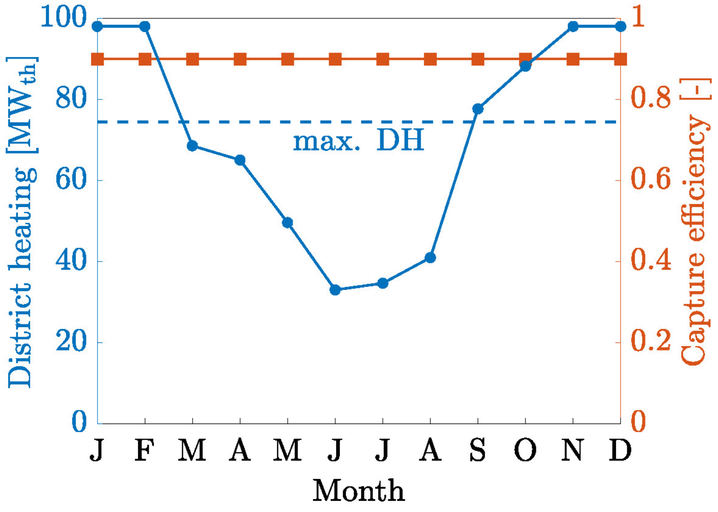
- Large amounts of waste heat available in summer
- 26% of heat sent to CCS can be directly recovered for district heating
- Seasonal capture possible
  - 55% of emitted CO_2 can be captured on average
  - Net-negative assuming 60% of MSW is biogenic
- Average electricity penalty is 25%

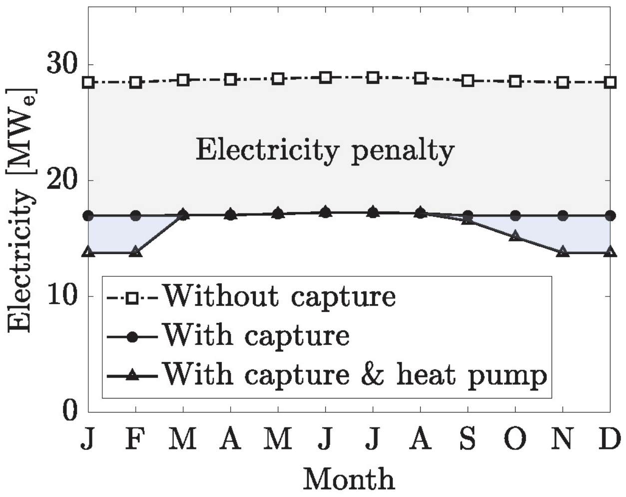
Otgonbayar et al, 2023, in preparation

Results - maximum CO_2 capture with heat pumps

INTRODUCTION | KVA HAGENHOLZ | CO_2 CAPTURE | **RESULTS** | CONCLUSION







- Send required heat to CCS for 90% CO_2 capture
- District heating demand not met in winter (shaded blue area)
- Heat pumps can recover low-grade heat
  - Coefficient of performance of 7.4 proposed by MAN Energy Solutions
- Average electricity penalty is 45%

Otgonbayar et al, 2023, in preparation

Conclusion

INTRODUCTION | KVA HAGENHOLZ | CO_2 CAPTURE | RESULTS | **CONCLUSION**

- KVA Hagenholz generates enough heat and electricity onsite to sustain a CO_2 capture and conditioning process **without compromising district heating,** even in winter
  - Negative emissions achievable by using only excess (waste) heat
  - Maximum capture can be carried out by providing missing district heat using large scale heat pumps
- Almost **half of the electricity generated onsite** is required for CO_2 capture

- After expansion of the third line, KVA Hagenholz will be responsible for **over 40% of Zurich's CO_2 emissions**
- These emissions need to be reduced in order to reach the Zurich's and Switzerland's net-zero goals
- From a technical point of view, **reducing and removing CO_2 is feasible** with good integration strategies that exploit synergies between CO_2 capture and district heating
- Capture and conditioning need to be integrated into a **whole supply chain**, considering among others:
  - Transport and logistics
  - Space requirements
  - Policy, costs and financing

Acknowledgements

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DEMO UP CARMA

Public perception of CO_2 management solutions in Switzerland

Energy Week @ETH 2023, 6th December 2023

Dr. Irina Dallo, ETH Zurich

Dr. Michèle Marti, ETH Zurich

Dr. Samuel Eberenz, Stiftung Risiko-Dialog

Matthias Holenstein, Stiftung Risiko-Dialog

The entire group: Lorena Kuratle (ETH Zurich), Stefanie Zeller (ETH Zurich), Công Ly (ETH Zurich), Prof. Dr. Stefan Wiemer (ETH Zurich)

DemoUpCARMA is funded and supported by the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN)

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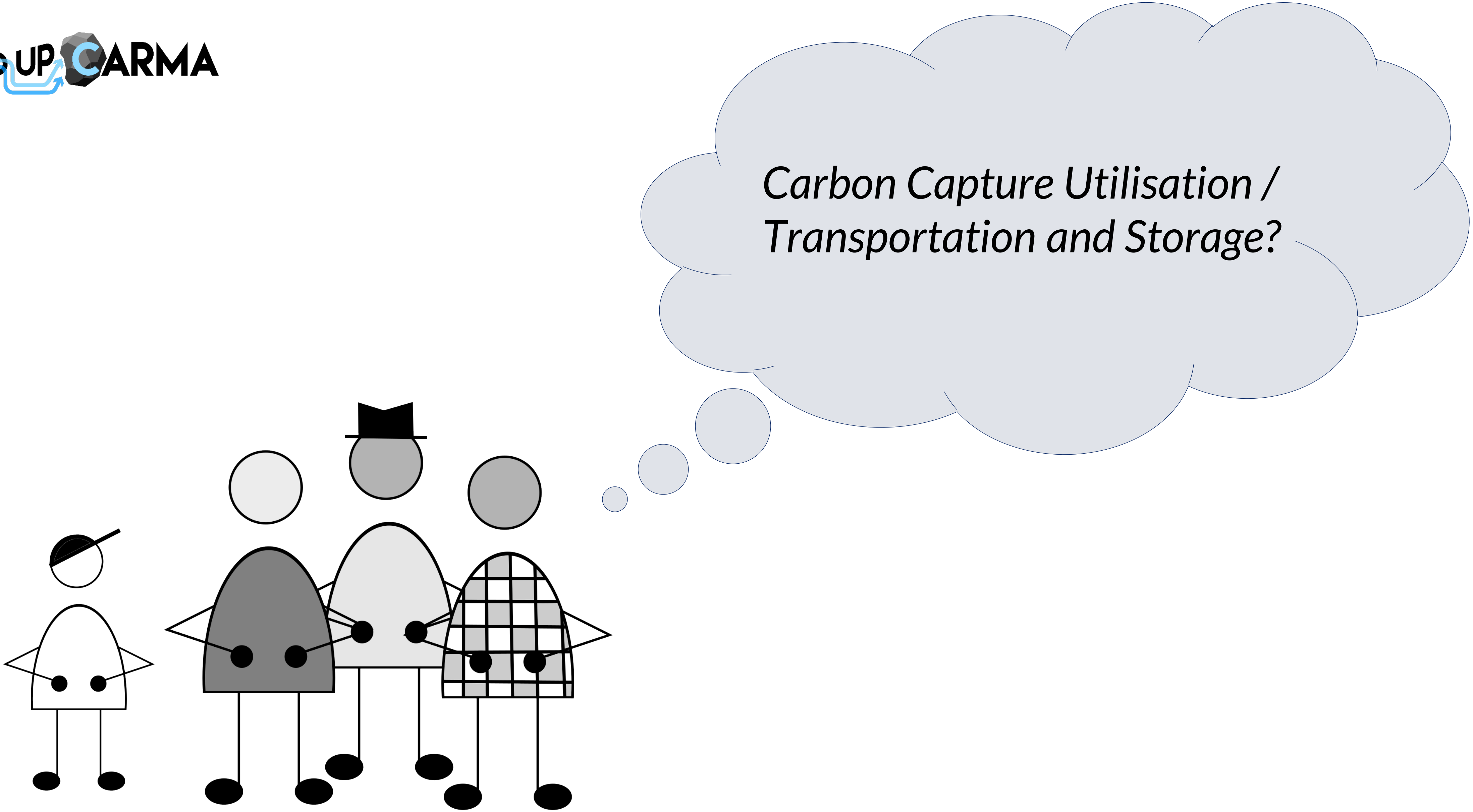
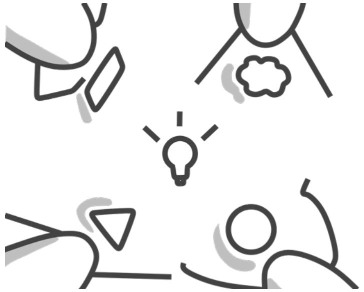


Carbon Capture Utilisation / Transportation and Storage?

Methodology – Target Audiences



Professional Stakeholders

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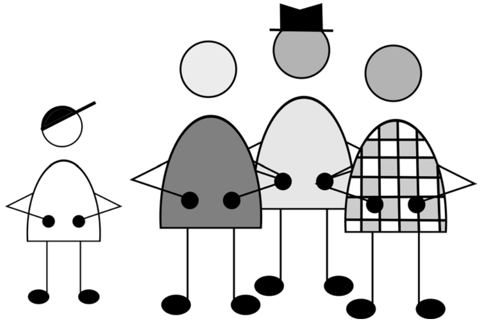
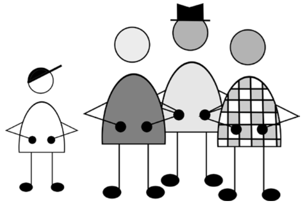


General Public

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Methodology – Research questions [CCTS/CCUS]



1) *Who are relevant stakeholder groups?*
2) *Which pretentions do Swiss stakeholders have?*
3) *What are stakeholders‘ interests, scopes of influence, and activities?*

1) *How familiar, supportive, and accepting is the Swiss public and how do they perceive potential risks and benefits?*
2) *How to design understandable communication products?*

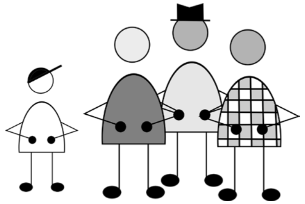
Methodology – Studies

Literature Research

Questionnaire (project internal) (N=14)

Semi-structured **interviews** (N=17)

Workshops and informal exchange



Literature Research

Focus groups (N=6) with 22 Swiss citizens

Representative online survey with between-subjects experiment (N=503)

Recommendations for *Communication to the public*

Establishing the **context**

Assessing public information **needs** continuously

Providing **hierachical** information

Providing specific **examples**

Providing **expert** opinions

Recommendations for *Communication to the public*

Assessing public information **needs** continuously

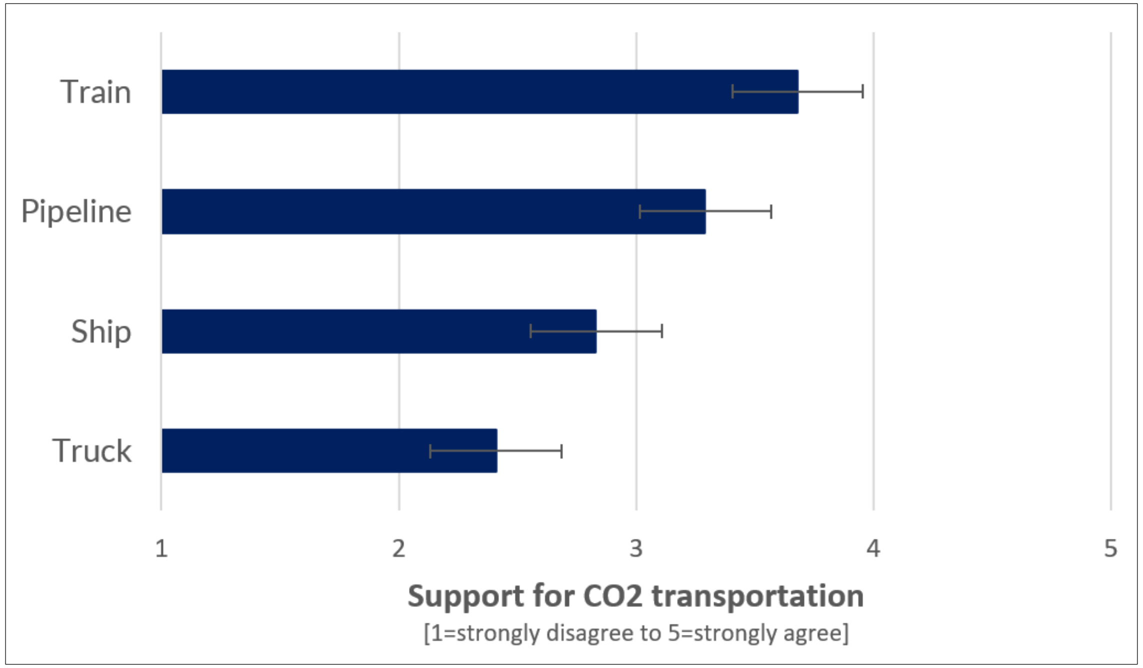


Figure 1: Overview of the support for the transportation means for CO_2 transport

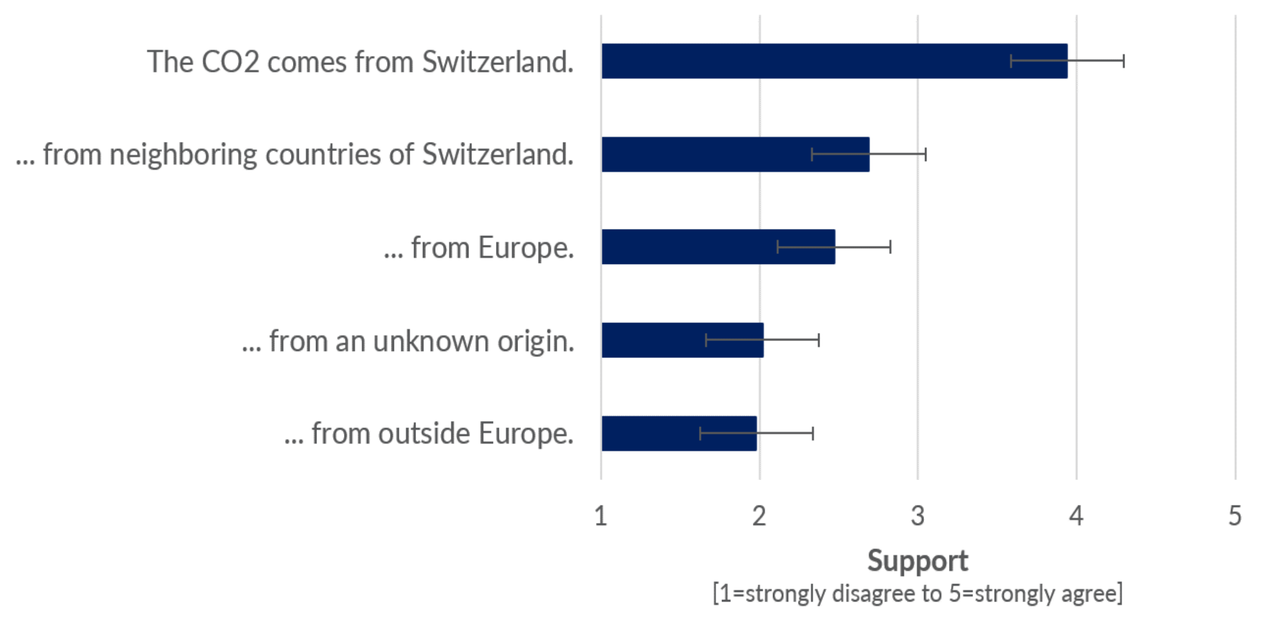
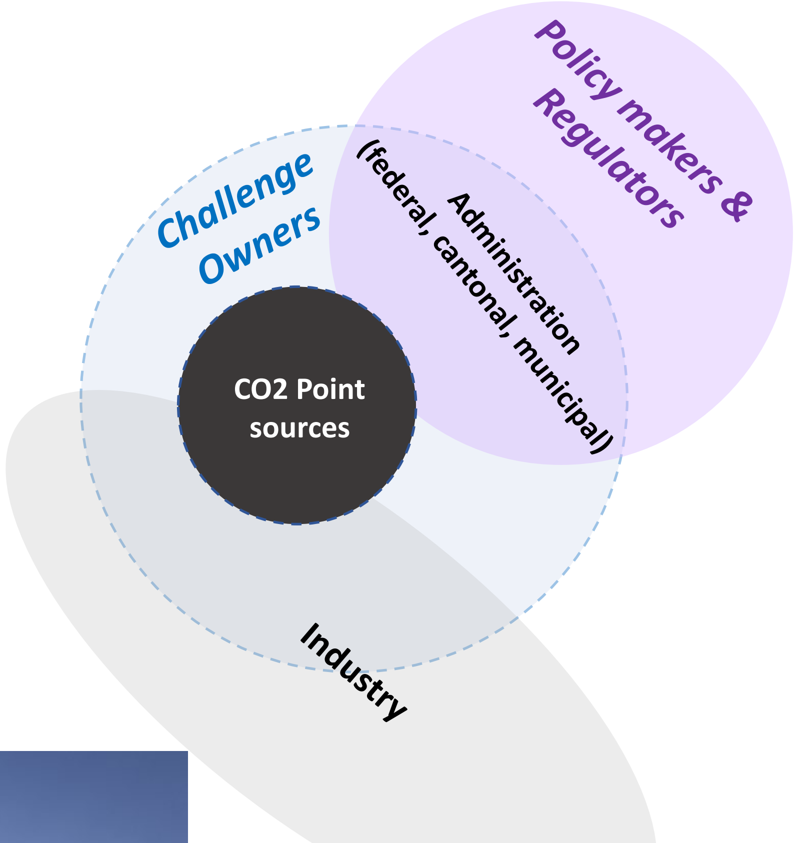


Figure 2: Support of CO_2 storage in Switzerland, when the CO_2 comes from the listed sources.

Mapping of relevant stakeholder groups for CCTS/CCUS in Switzerland



Policy makers & Regulators

Challenge Owners

Administration (federal, cantonal, municipal)

CO2 Point sources

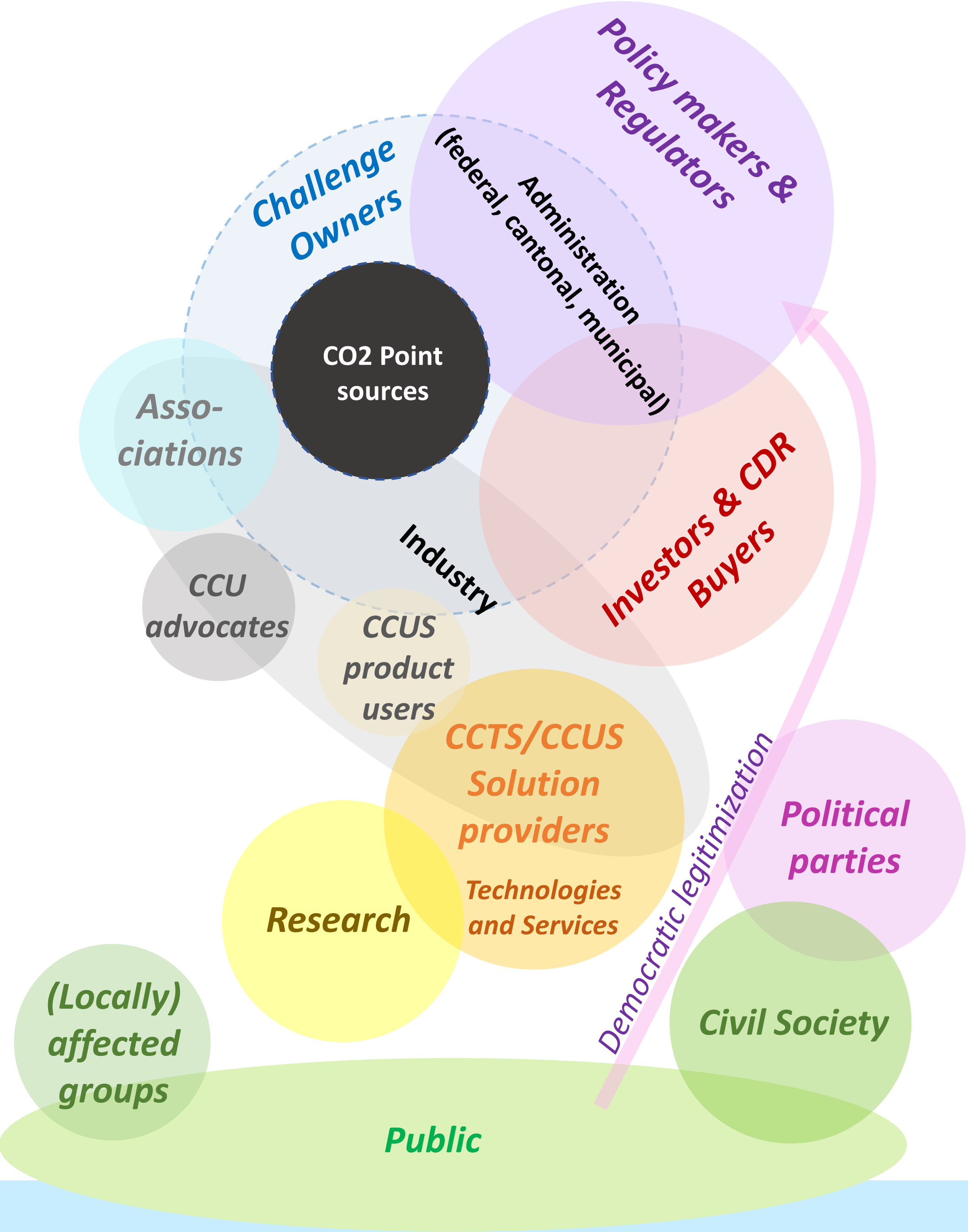
Industry

Source: zh.ch

Source: srf.ch

Source: airfixcarbon.com

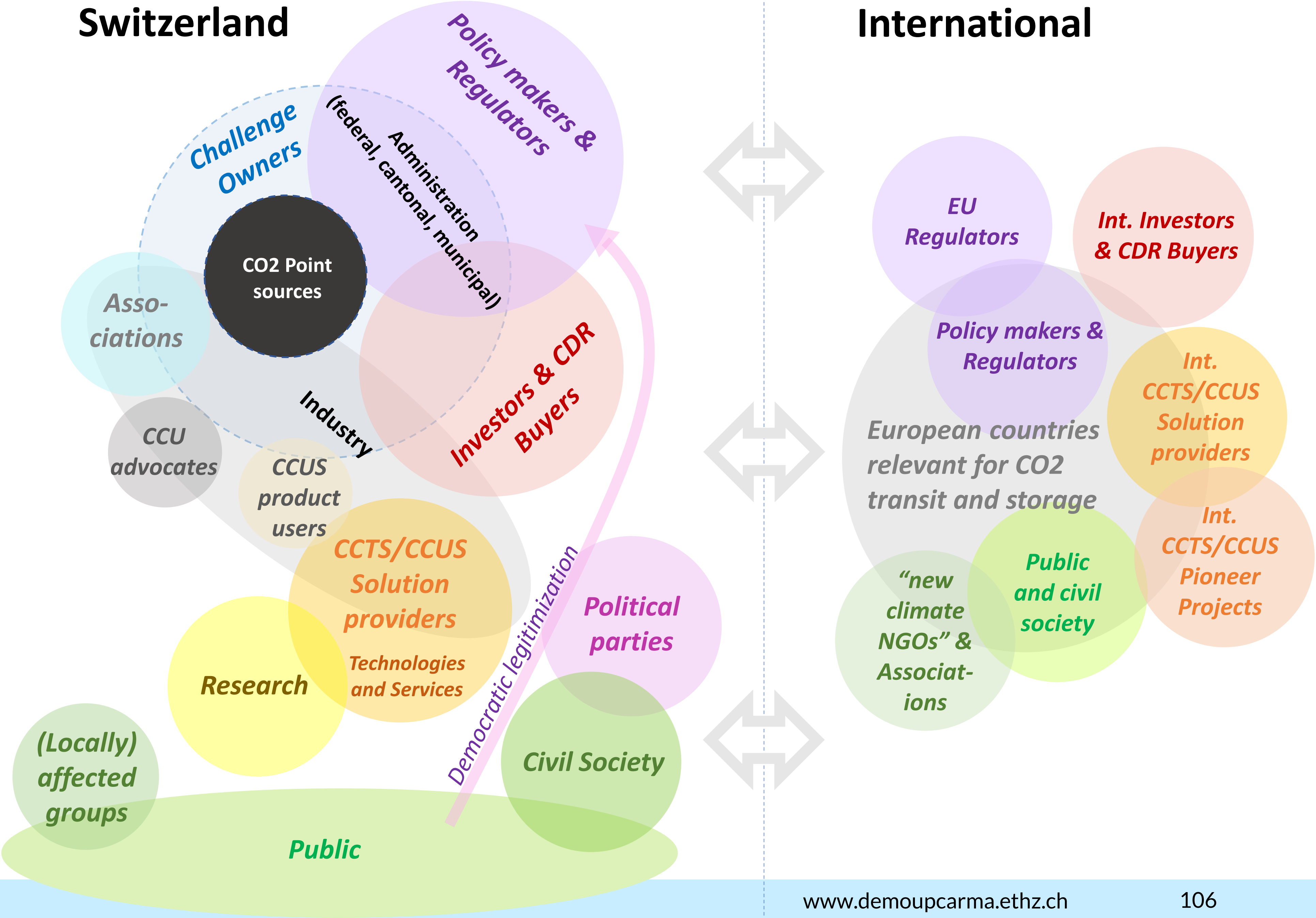
Mapping of relevant stakeholder groups for CCTS/CCUS in Switzerland



Mapping of relevant stakeholder groups for CCTS/CCUS in Switzerland and internationally

Switzerland

International



Policy makers & Regulators

Challenge Owners

Administration (federal, cantonal, municipal)

CO2 Point sources

Asso-ciations

Industry

Investors & CDR Buyers

CCU advocates

CCUS product users

CCTS/CCUS Solution providers

Technologies and Services

Research

Democratic legitimization

Political parties

Civil Society

(Locally) affected groups

Public

EU Regulators

Int. Investors & CDR Buyers

Policy makers & Regulators

European countries relevant for CO2 transit and storage

Int. CCTS/CCUS Solution providers

Int. CCTS/CCUS Pioneer Projects

"new climate NGOs" & Associat-ions

Public and civil society

Recommendations for *Stakeholder ngagement*

- Involving **relevant** stakeholder groups
- **Differentiating** the systemic challenge and specific implementation
- **Differentiating** advocates, observers, cautioners, and the uninformed
- Adapting **engagement** strategies in a dynamic context

Conclusion

Transparent communication and inclusive decision-making are key to:

- Anticipate and mitigate **hurdles and risks** in implementing CO_2 management solutions in a complex system;
- Enable informed formation of public opinion for **democratic decision-making**;
- Contribute to **procedural justice** and long-term **sustainability**.

Thank you for your attention!

Find out more

- **Deliverable 5.5 – Stakeholder mapping**
  [Samuel Eberenz, Matthias Holenstein, Carmela Cavegn, Irina Dallo]
- **Deliverable 5.6 – Swiss public perception towards CCTS and CCUS**
  [Irina Dallo, Michèle Marti, Lorena Kuratle, Công Ly, Simone Zaugg, Stefanie Zeller]
- Scientific publications in preparation

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Public perspective: Dr. Irina Dallo (irina.dallo@sed.ethz.ch)

(Reflections on) the Role of Carbon Markets

Matthias Honegger

Senior Research Associate, Perspectives Climate Research

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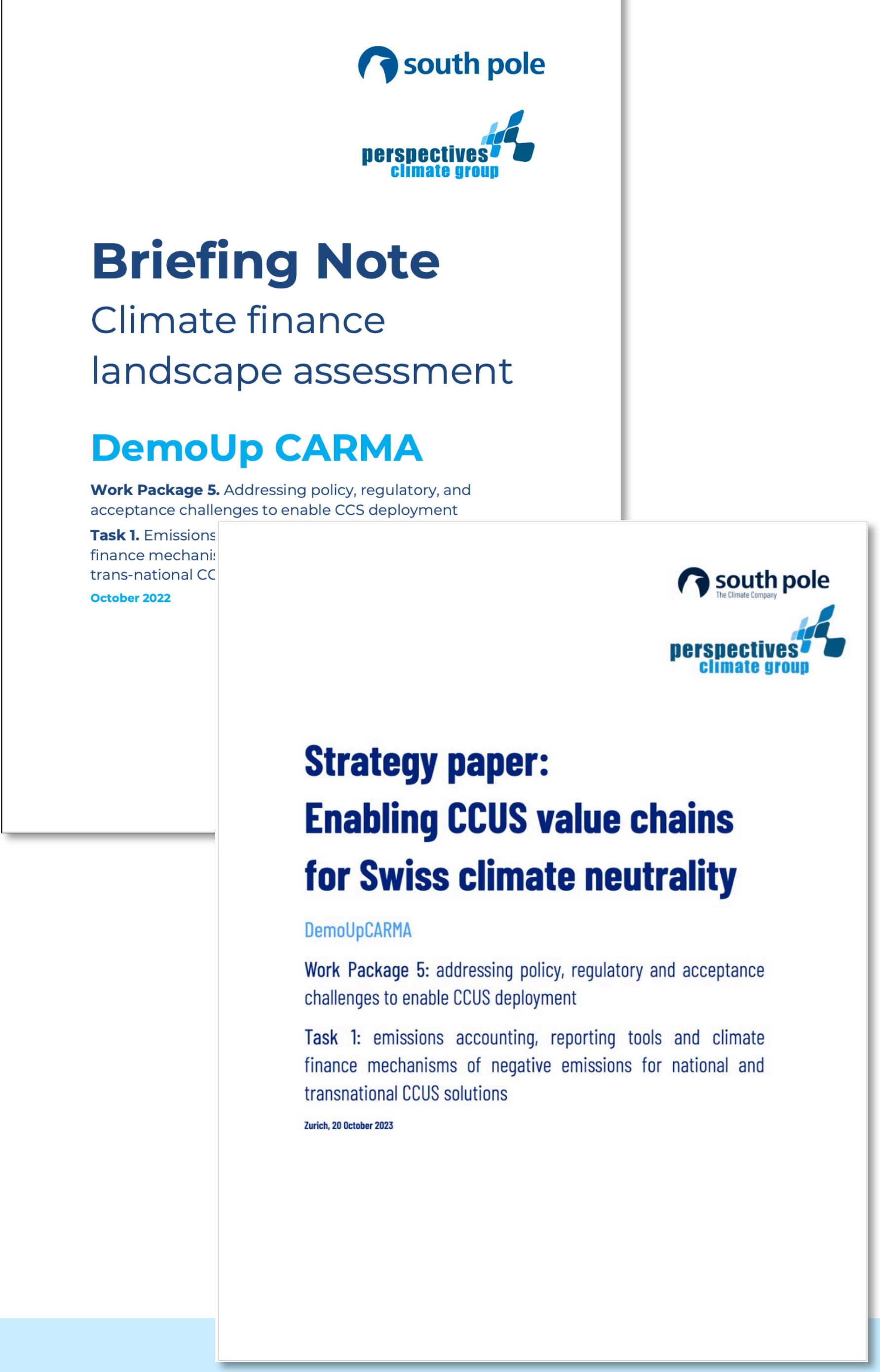
How is CCS and CCUS to be paid for?

- Two options:
  - to force (regulation) or
  - to fund (CHF)
- Carbon Markets: an avenue to generate „carbon revenue“
- **Payment for** Mitigation **Results** from industry, energy and waste:
  - Relative reductions in CO_2 emissions, or
  - Removal of CO_2 (CDR)
- Carbon Markets are a tool to move funds in return for results
- But they are only as good as the
  - rules – determining credibility and integrity
  - demand of buyers of certificates



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Briefing Note

Climate finance
landscape assessment

DemoUp CARMA

Work Package 5. Addressing policy, regulatory, and acceptance challenges to enable CCS deployment

Task 1. Emissions
finance mechani
trans-national CC

October 2022

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Strategy paper:
Enabling CCUS value chains
for Swiss climate neutrality

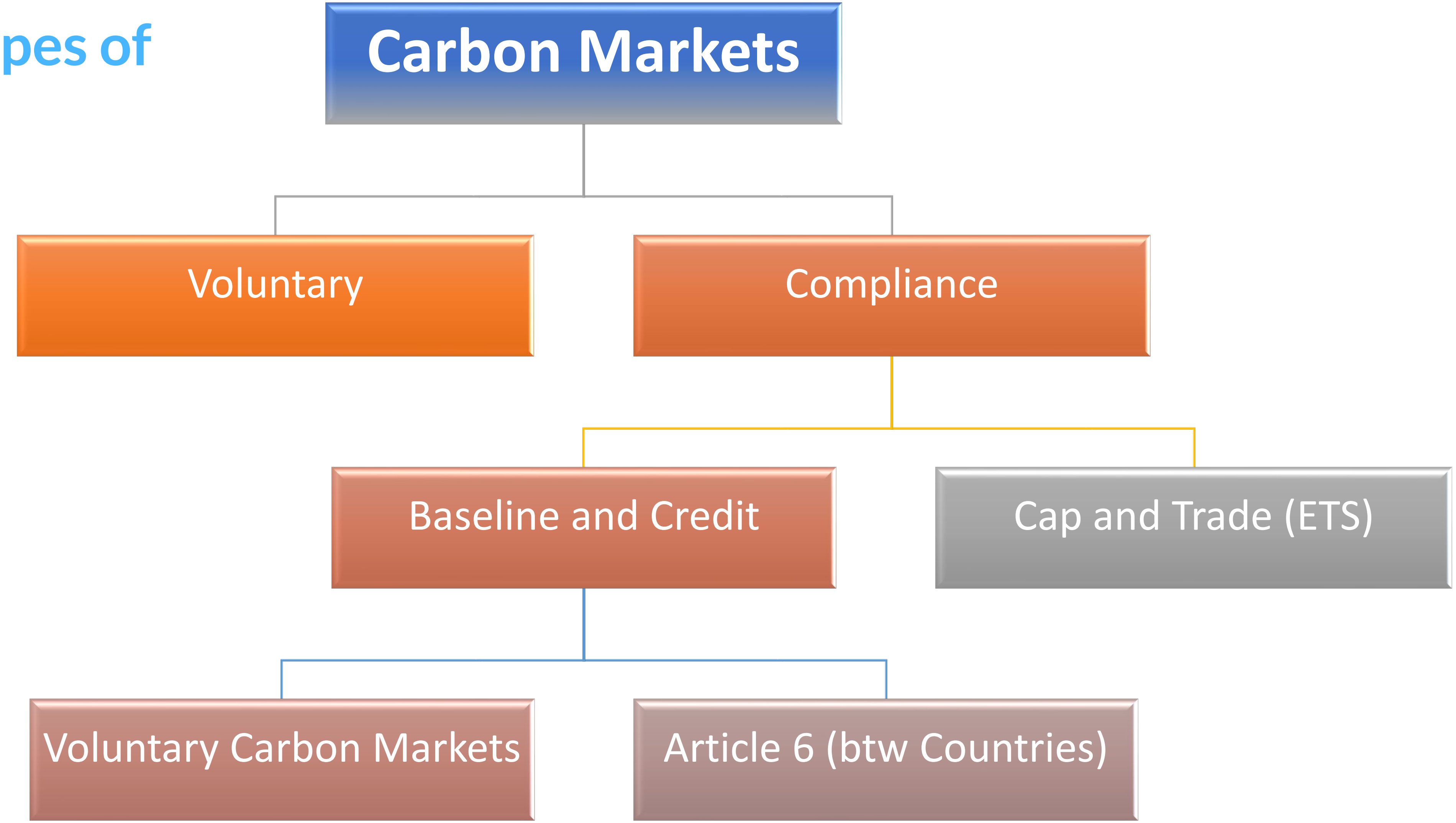
DemoUpCARMA

Work Package 5: addressing policy, regulatory and acceptance challenges to enable CCUS deployment

Task 1: emissions accounting, reporting tools and climate finance mechanisms of negative emissions for national and transnational CCUS solutions

Zurich, 20 October 2023

Types of



Carbon Markets

Voluntary

Compliance

Baseline and Credit

Cap and Trade (ETS)

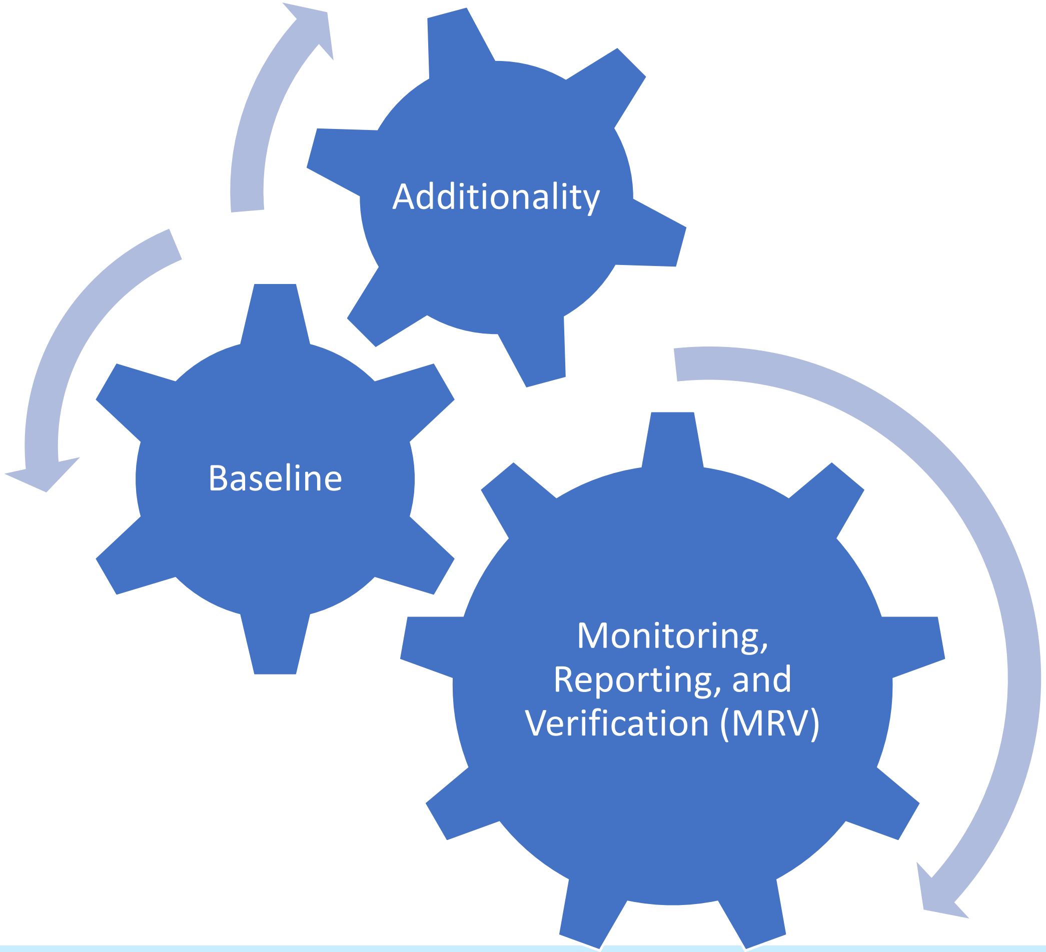
Voluntary Carbon Markets

Article 6 (btw Countries)

Baseline and Credit Markets (VCM & Paris Article 6)

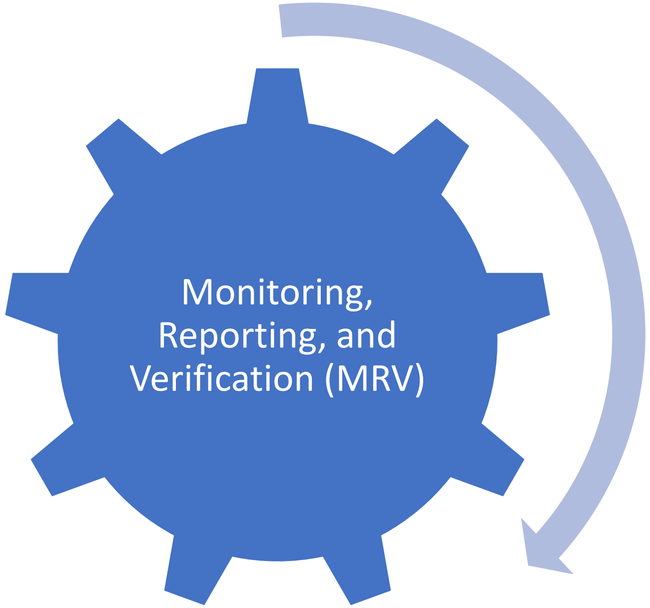
Share the same core mechanics:

Credit the MRV'd mitigation results compared to the appropriate baseline if activity is additional (i.e. only became possible through carbon revenue).



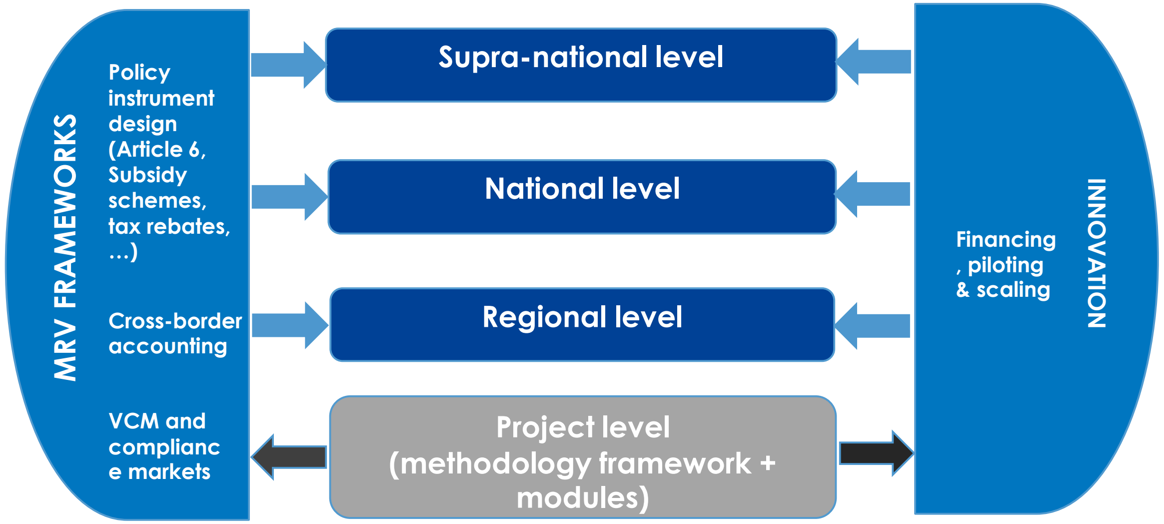
Methodologies for MRV – first developed for Voluntary Market

- So far MRV has been narrow (single application type)
- Modular approach of CCS+ allows uncountable (re-)combinations across the many elements of CCS and CCUS (including novel ones for various forms of DACS and BECCS)
  - 2 framework methodologies –
    - one for CCS and another for CCU
  - 6 different capture modules
  - All possible means of transport
  - 6 geological storage and long-term utilisation modules



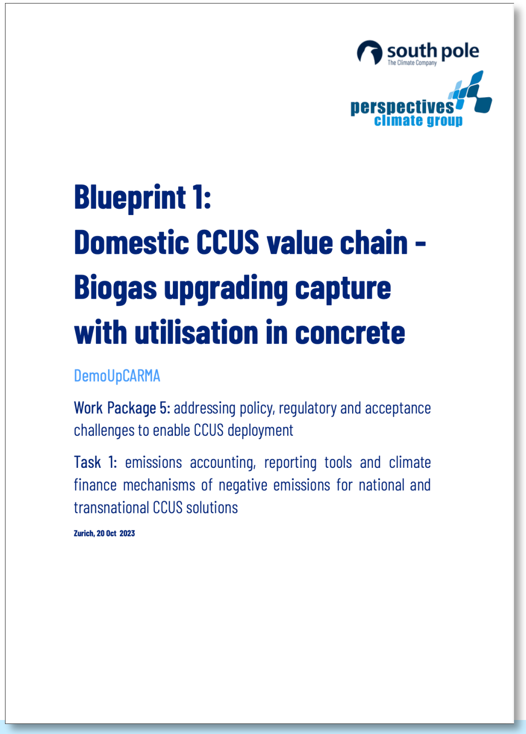
Broader Relevance of MRV for ETS and International trading

- Comprehensive MRV enables results-based transactions
- Regulators are looking for examples and guidance
    - EU Commission (regarding CRCF and CCS Directive)
    - US Department of Energy



How to get going then?

Blueprints with guidance for specific examples:



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Blueprint 1:
Domestic CCUS value chain - Biogas upgrading capture with utilisation in concrete

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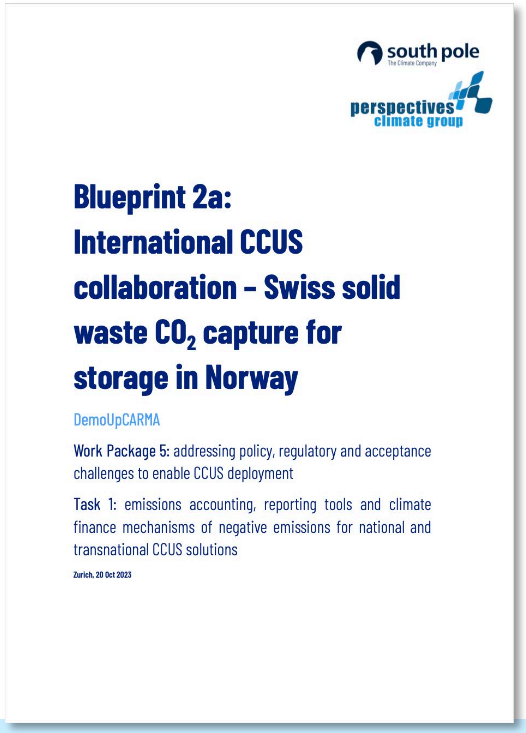
Work Package 5: addressing policy, regulatory and acceptance challenges to enable CCUS deployment

Task 1: emissions accounting, reporting tools and climate finance mechanisms of negative emissions for national and transnational CCUS solutions

Zurich, 20 Oct 2023



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Blueprint 2a:
International CCUS collaboration – Swiss solid waste CO_2 capture for storage in Norway

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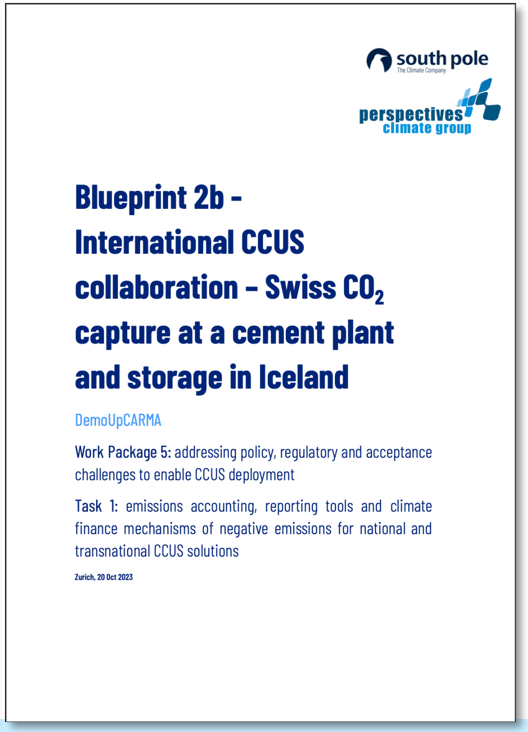
Work Package 5: addressing policy, regulatory and acceptance challenges to enable CCUS deployment

Task 1: emissions accounting, reporting tools and climate finance mechanisms of negative emissions for national and transnational CCUS solutions

Zurich, 20 Oct 2023



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Blueprint 2b -
International CCUS collaboration – Swiss CO_2 capture at a cement plant and storage in Iceland

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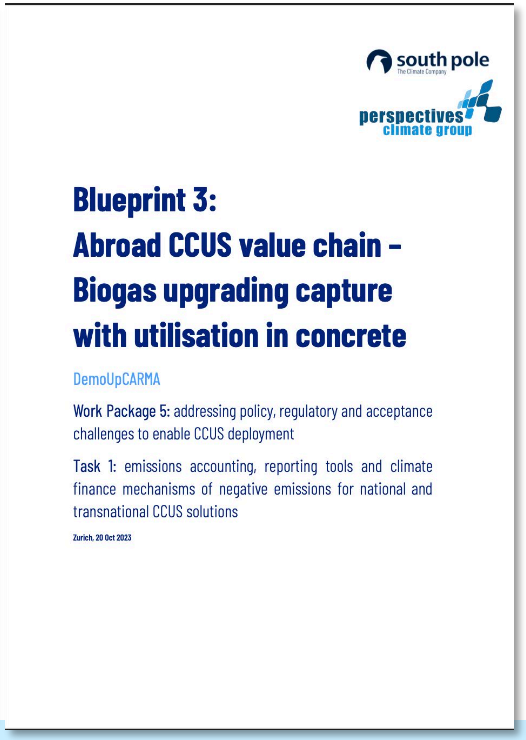
Work Package 5: addressing policy, regulatory and acceptance challenges to enable CCUS deployment

Task 1: emissions accounting, reporting tools and climate finance mechanisms of negative emissions for national and transnational CCUS solutions

Zurich, 20 Oct 2023



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Blueprint 3:
Abroad CCUS value chain - Biogas upgrading capture with utilisation in concrete

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Work Package 5: addressing policy, regulatory and acceptance challenges to enable CCUS deployment

Task 1: emissions accounting, reporting tools and climate finance mechanisms of negative emissions for national and transnational CCUS solutions

Zurich, 20 Oct 2023

Energy Week @ ETH 2023

CO_2 transport, and financing of the infrastructure

ETH Zürich, Switzerland
6th December 2023

Pauline Oeuvray, Institute of Energy and Process Engineering, ETH Zurich
Katrin Sievert, Climate Finance and Policy Group and Institute of Science, Technology & Policy, ETH Zurich,

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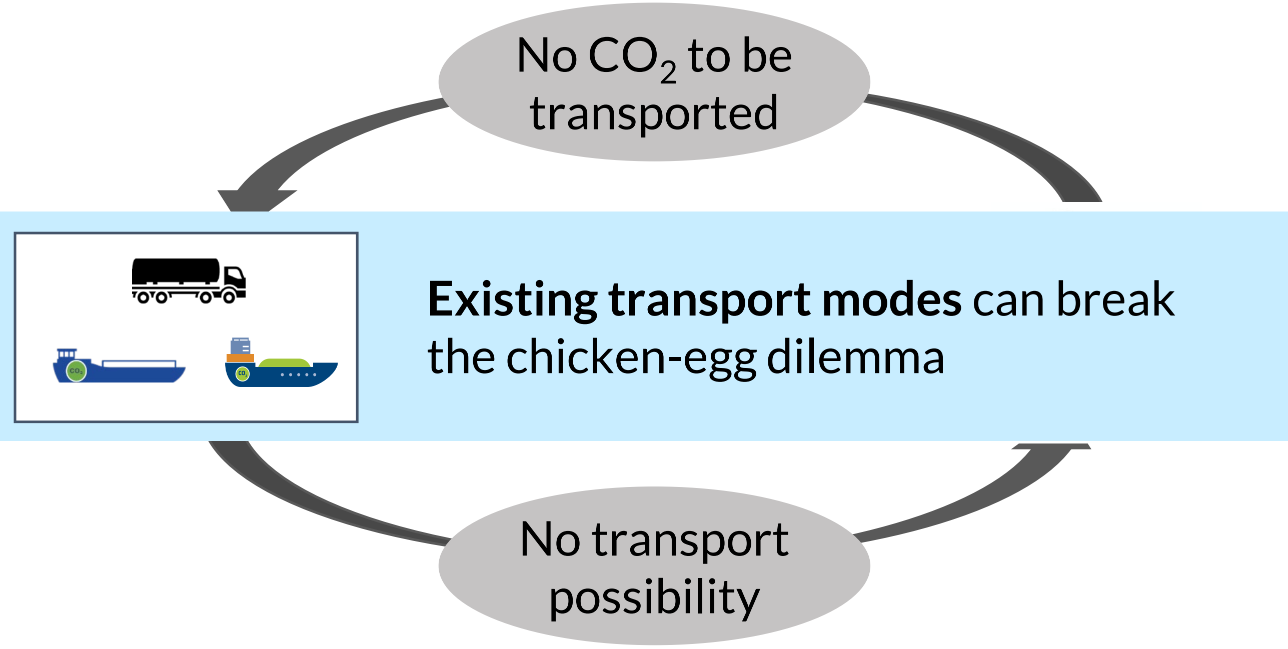
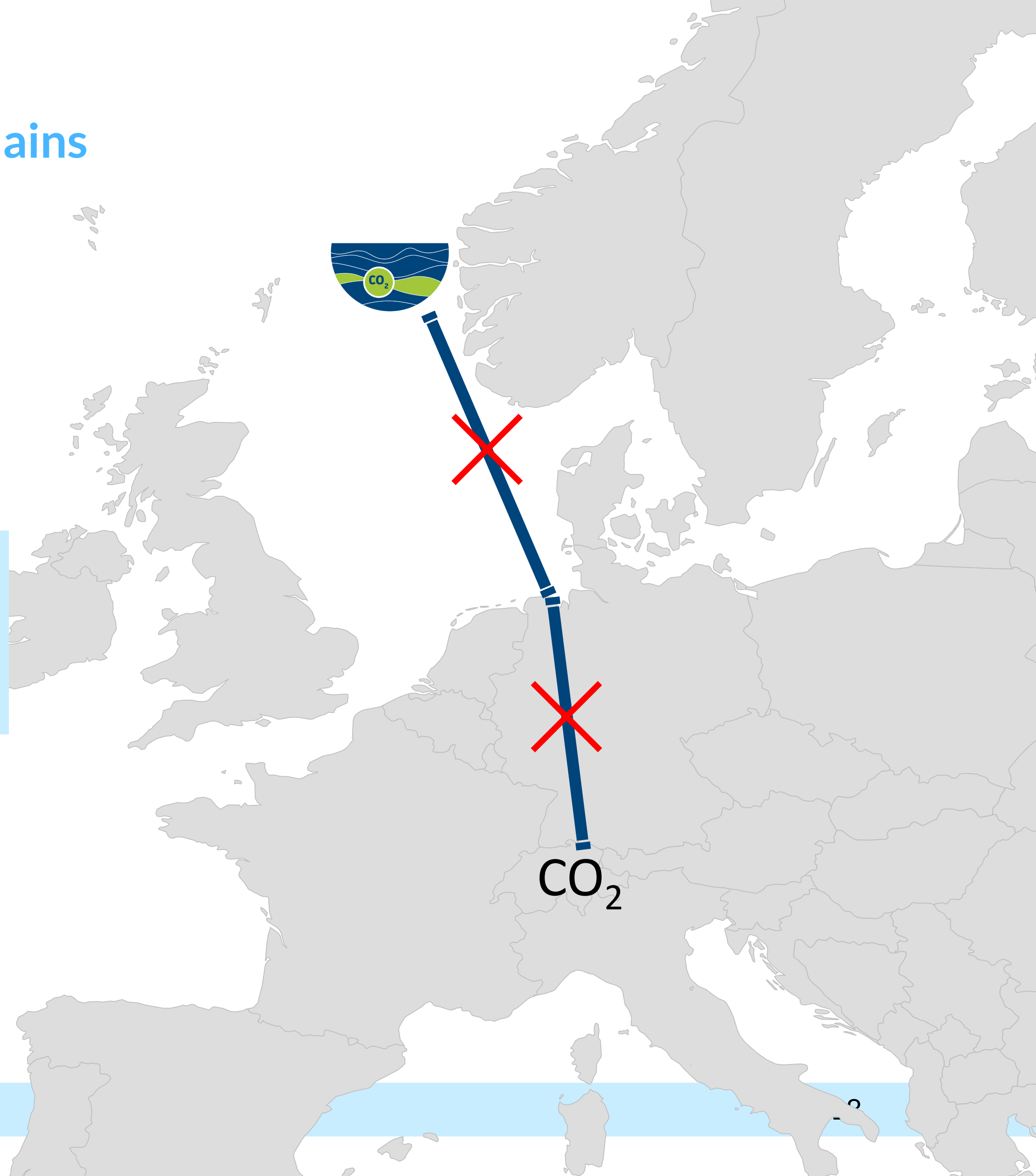
Inland CO_2 point sources need pioneering supply chains



No CO_2 to be transported

Existing transport modes can break the chicken-egg dilemma

No transport possibility



Options for CO_2 transport

Near term

Tank container

ISO tank container (source: DemoUpCARMA)

Medium (16 bar) pressure liquid

✓ ✓ ✓ ✓

20 t

Medium term

Dedicated transport

Rail Tank Car (source: NorthWoodsHiawatha, Attribution, via Wikimedia Commons)

Low (8 bar) or medium (16 bar) pressure liquid

✓	✓	🔍	🔍
26 t	50 t	3 000 – 5 000 t	5 000 – 50 000 t

Long term

Pipeline

Pipeline (source: US Government agent, Public domain, via Wikimedia Commons)

Gaseous (10-30 bar) or liquid (80-350 bar)

✓

No limitation

✓ Existing technology 🔍 Technology under development

CCTS at KVA Hagenholz for 2030

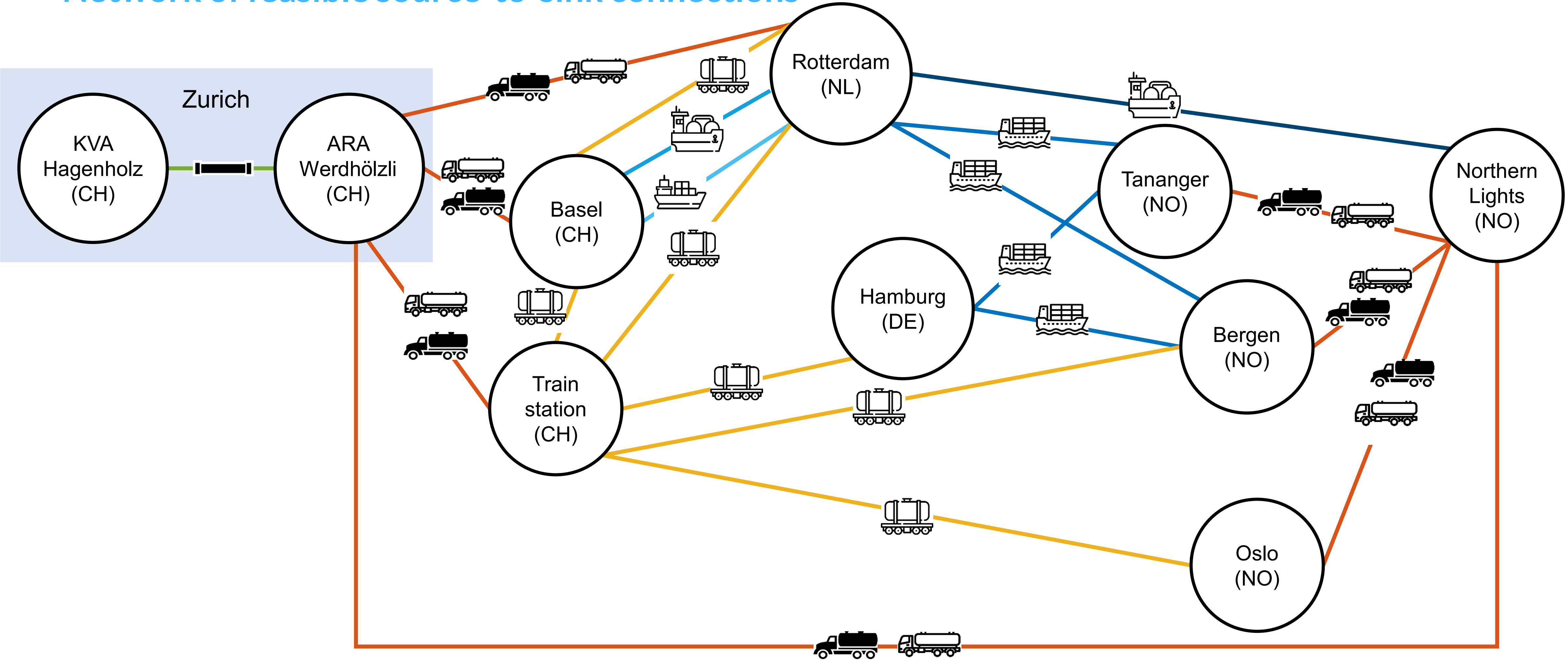
Waste-to-energy plant in Zurich (CH)

Emissions: ca. 400 000 tCO_2/y (Third line of incineration from 2027)

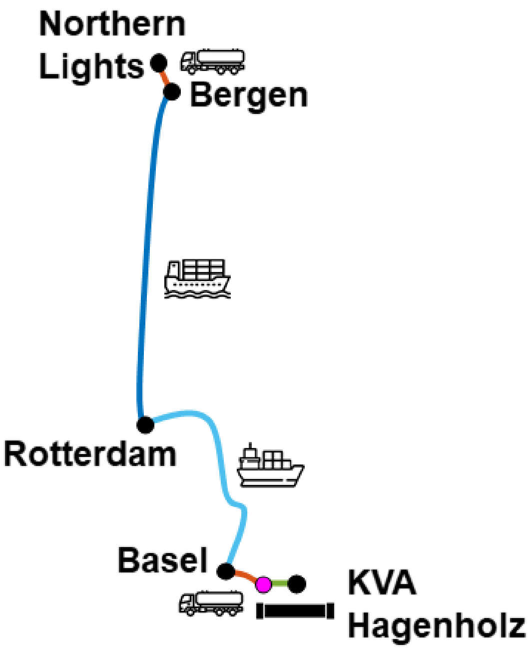
Kehrichtverwertungsanlagen im Kanton Zürich, https://www.zh.ch/de/umwelt-tiere/abfall-rohstoffe/abfaelle/abfallanlagen/kehrichtverwertungsanlagen.html

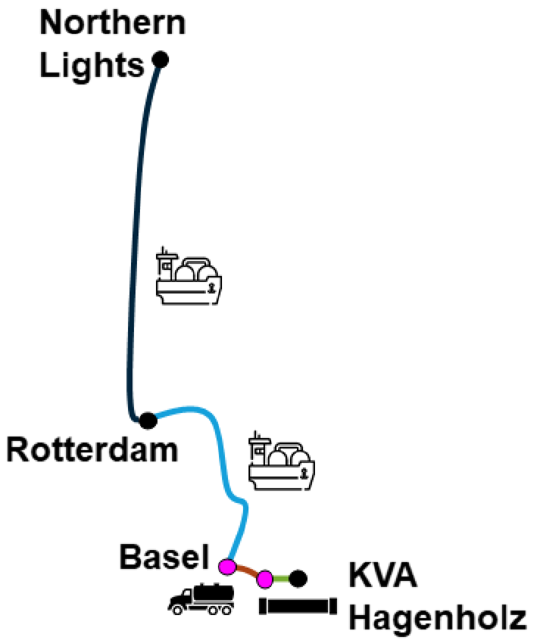
openstreetmap.org

Network of feasible source-to-sink connections



Two cost-effective supply chains

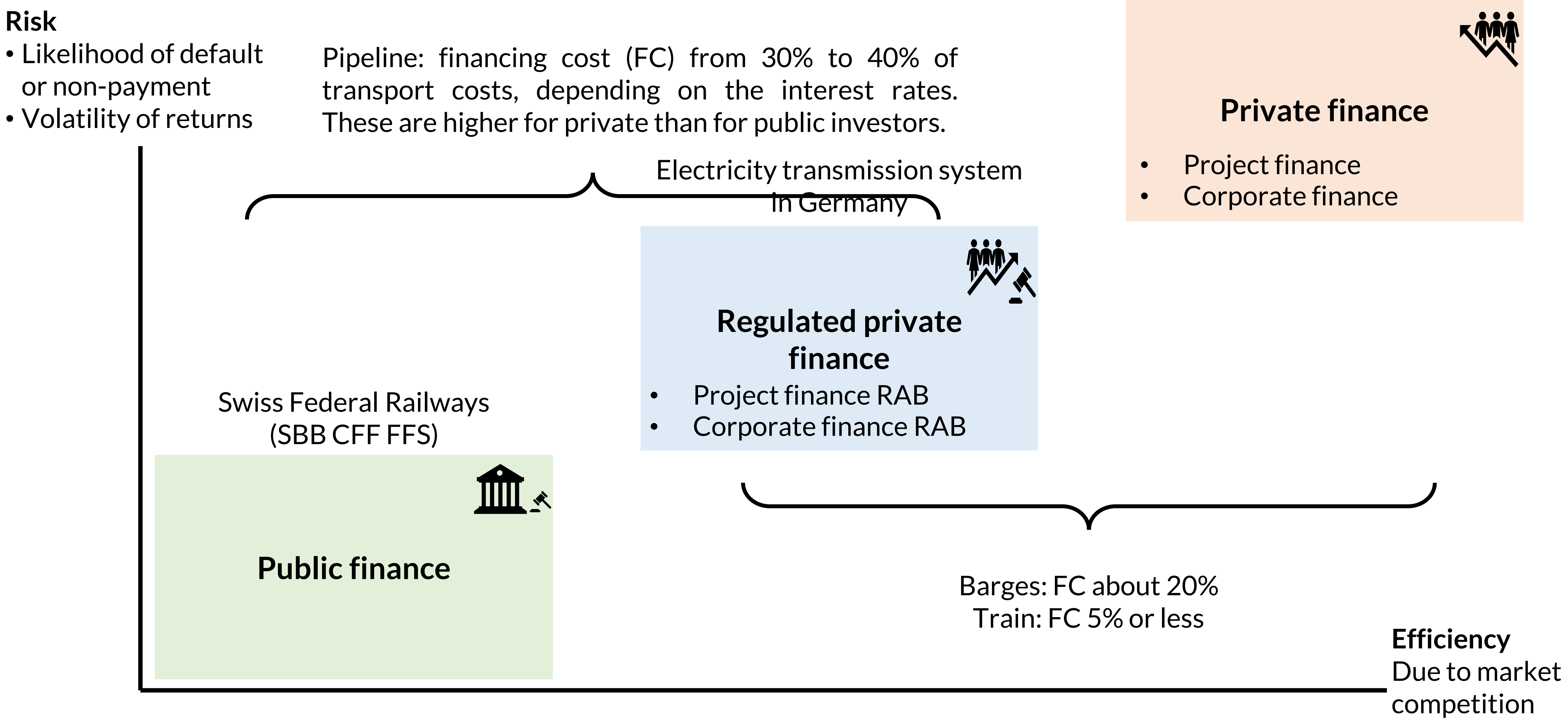




Transport pathway (± ca. 10%)	Near-term container-based solution	Medium-term dedicated transport solution
Levelized costs of transport [EUR/t]	160	80
Levelized cost of whole supply chain [EUR/t]	360	280
Transport emissions [$tCO_2eq/t_{transported}$]	15%	10%

Burger, Nöhl, Seiler, Gabrielli, Oeuvray, Becattini, Reyes-Lúa, Riboldi, Sansavini, Bardow, **2023**, *submitted*
Oeuvray, Burger, Roussanaly, Mazzotti, Becattini, **2023**, *submitted*

Impact of financing costs



Risk

- Likelihood of default or non-payment
- Volatility of returns

Pipeline: financing cost (FC) from 30% to 40% of transport costs, depending on the interest rates. These are higher for private than for public investors.

River barges and ships

Private finance

- Project finance
- Corporate finance

Electricity transmission system in Germany

Regulated private finance

- Project finance RAB
- Corporate finance RAB

Swiss Federal Railways (SBB CFF FFS)

Public finance

Barges: FC about 20%
Train: FC 5% or less

Efficiency
Due to market competition

Conclusions & key take-aways

- Before a CO_2 pipeline network is built, **transport solutions based on existing technologies** are necessary.
- CO_2 can be transported in **tank containers** or **dedicated transport modes** on roads, on rail, along rivers and at sea.
- Many options are available for each emitter, and the most suitable ones can be identified based not only on **technical and economic considerations**, but also on **environmental and risks/resilience criteria**.
- Financing matters especially for **capital-intensive assets** such as pipelines, and it can make up a significant share of the total transport cost depending on **the type of investors** and **the general economic context.**

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MARIE CURIE ACTIONS

European Commission | Horizon 2020 European Union funding for Research & Innovation

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Panel discussion

Guests:

Dr. Viola Becattini – ETH Zurich

Dr. Sophie Wenger – Federal Office for the Environment

René Estermann – Director, Environment and Health Department, City of Zurich

Mario Davidi – Waste Management and Recycling, City of Zurich

Moderator: Dr. Benedikt Knüsel – ETH Zurich