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Geoscience for a sustainable Earth

PROSPECTIVE INTEGRATION OF GEOTHERMAL ENERGY WITH CARBON CAPTURE AND STORAGE

Webinar – 09/27/2023

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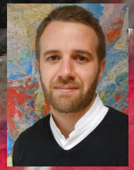


INTRODUCTION

Main objectives of the study

Provide objective answers to the following questions:

1) What type of hybrid CCS/geothermal systems are operational and/or described in the literature?
2) What are the main criteria that should be considered to enable comparison of these systems?
3) Which regions have the most favourable features for future implementation of these technologies?

LITERATURE REVIEW OF CONCEPTS AND PROJECTS COMBINING GEOTHERMAL ENERGY AND CCS

CLASSIFICATION OF THE CONCEPTS

1 — USE OF SUPERCRITICAL CO_2 AS HEAT VECTOR FOR GEOTHERMAL EXPLOITATION AND/OR ENERGY STORAGE

2.1 — WATER-DRIVEN GEOTHERMAL HEAT EXTRACTION WITH CO_2 INJECTION TO ACHIEVE NEAR-ZERO CO_2 GEOTHERMAL PRODUCTION

2.2 — WATER-DRIVEN GEOTHERMAL HEAT EXTRACTION WITH INJECTION OF CO_2 IN THE DISSOLVED FORM FOR CCS

3 — OTHER SYNERGIES (THE GEOTHERMAL FLUID AND CO_2 FOR CCS ARE HANDLED SEPARATELY)

4 — OTHER BORDERLINE CONCEPTS (OUT OF STUDY SCOPE)

LEGEND

Depth

Temperature

M — Mainly mineral trapping (rapid mineralization of CO_2)

D — Mainly solubility trapping (CO_2 dissolved in brine)

S — Mainly structural trapping (e.g. below a tight caprock)

Geothermal power plant (heat &/or electricity)

External CO_2 emitter

Hybrid power plant (geothermal & other)

H_2O Water tank

Gas engine (heat &/or electricity)

Mainly water Or brine

Mainly CO_2

H_2O Brine

Sc CO_2 Supercritical CO_2

Brine with dissolved CO_2

liq CO_2 Liquid CO_2

Water steam with gas CO_2

CO_2 (e.g. gas phase)

TECHNO-ECONOMIC COMPLEXITY. Considering non-comparable or non-available economic information, we resort to qualitative complexity assessment concerning technico-economic complexity.

Wells drillings (high number, high depth vs. more simple layout)

Stimulation required

System initialization required

Geochemistry management (complex issues vs. accessible issues)

Complex system (either underground or at surface installations)

Sc CO_2 Free phase of buoyant CO_2, thus requiring efficient confinement

Seismicity issue

Integration in electricity network for storage

H_2O ? Water not entirely reinjected, should be managed.

Use/share already existing infrastructures

DEFINITION OF THE INDEXES OF SERVICES RATIO

Foreword:

The proposed index has been elaborated for the purpose of the present study only. It aims at conveying an order of magnitude and enabling comparison between concepts. It does not claim to be a rigorous economic indicator.

1 MtCO2 stored over 30 years → **30 M$** [Moderate CO2 price from IEA: 30 $/tCO2]

Electricity production with power capacity 1 MWe → **30 M$** [114$/MWe, picked in the LCOE reasonable range for renewable electricity production]

Thermal production with capacity 3 MWth → **30 M$** [Default IEA assumtion: 37 $/MWth]

$$I_{CS} = \frac{Q_{CO2}}{Q_{CO2} + P_e + \frac{P_{th}}{3}}$$

$$I_e = \frac{Pe}{Q_{CO2} + P_e + \frac{P_{th}}{3}}$$

$$I_{th} = \frac{\frac{P_{th}}{3}}{Q_{CO2} + P_e + \frac{P_{th}}{3}}$$

IEA, 2020. Projected Costs of Generating Electricity - 2020 Edition.

CLASSIFICATION OF THE CONCEPTS

1

USE OF SUPERCRITICAL CO_2 AS HEAT VECTOR FOR GEOTHERMAL EXPLOITATION AND/OR ENERGY STORAGE

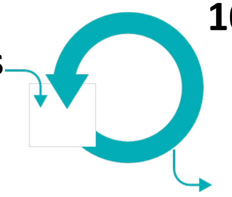
CPG – CO_2 Plume Geothermal

1 - 4 km

80 to 200°C

External input 5-30 kg/s

Supercritical CO_2 100-300 kg/s



5-10% loss

+

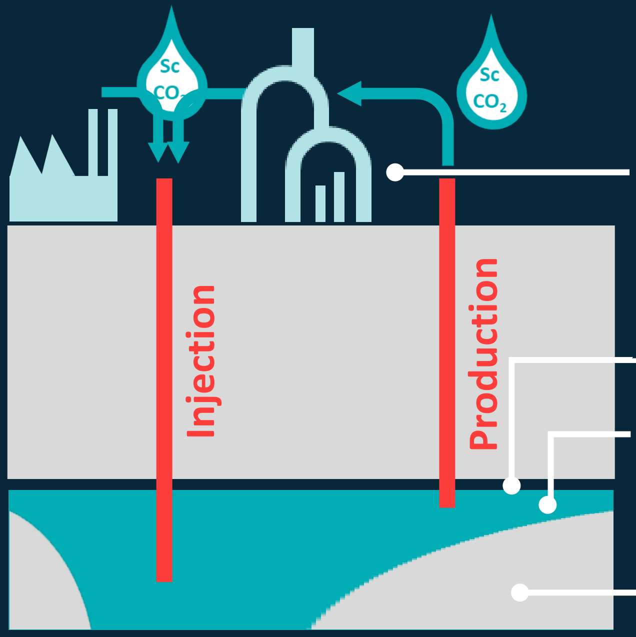
Outstanding performances by combining non-intermittent renewable energy production and CO_2 storage from external emitter
Wide potential of replicability .
Efficiency higher with Sc-CO_2 than with water

−

High investment cost
Needs Initialization (Months or year)
Tricky design for long-term exploitation
CO_2 confinement and leakage risk issue

TRL

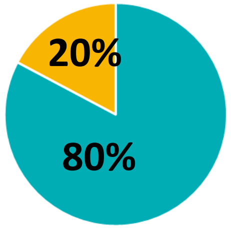
First paper in 2011, a patent in 2012
Tens of modeling papers by different teams
No pilot, but CCS demonstrators give promising insights in feasibility.
Cradle: US



CPG consists of using supercritical CO_2 ($ScCO_2$) instead of brine as heat vector in hydrothermal reservoirs (porous and permeable sedimentary formation) to produce geothermal energy (generally electricity).
The concept requires drilling (generally 1-4 km), at least a doublet (1 injector & 1 producer), then initialization of the system until CO_2 plume creation reaching the production well.
For most conditions, the energy efficiency is higher with CO_2 than with water/brine due to higher mobility and thermosiphon effect. Efficiency improvement around +50% - +200% might be expected.
The high enthalpy CO_2 can be used either directly in a CO2-compatible turbine or through a binary cycle with a heat exchanger. CO2 is then cooled and compressed before reinjection.
Continuous external inflow of CO_2 is co-injected in order to compensate fluid loss in the reservoir (estimated around 5-10 % of the total flow). If the CO2 remains confined at depth, it leads to huge amount of CO_2 storage after 30 years of operation.

SERVICES PROVIDED

- Energy Production
  - 1 – 6 MWe
- CO2 Storage
  - 5 – 30 Mt CO_2 over 30 years
- Energy Storage Service



Index of services ratio
(defined with economical assumptions within the study)

IMPLEMENTATION COMPLEXITY

2-5 wells

Initialization (months or year)

Confinement Sc CO_2

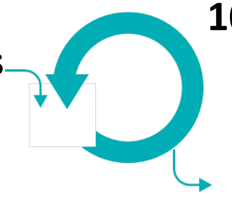
CO_2-EGS – Enhanced Geothermal System

3 - 6 km

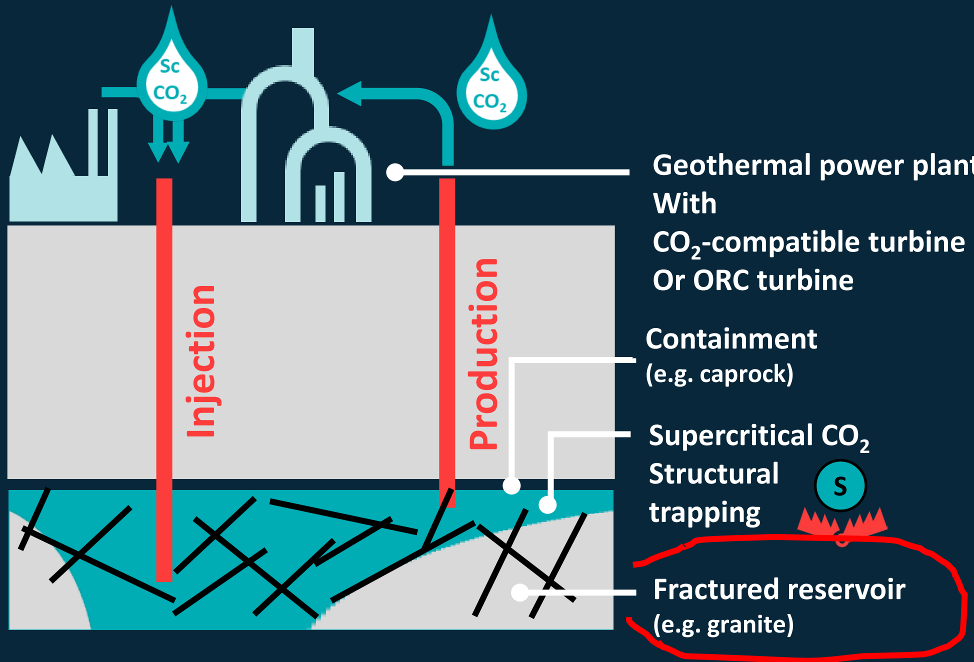
160 to 300°C

External input 5-15 kg/s

Supercritical CO_2 100-300 kg/s



5% loss



+

Outstanding performance by combining non-intermittent renewable energy production and CO_2 storage from an external emitter
Efficiency higher with Sc-CO_2 than with water

–

High investment cost
High development risks
Tricky design for long-term exploitation
CO_2 containment and risk/impact issues

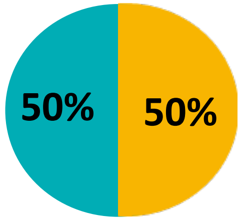
TRL

First paper in 2000 (Brown)
Tens of modelling papers by different teams (mainly: case studies, underground modelling, geochemical modelling, system modelling)
Cradle: US

CO_2-EGS consists in using supercritical CO_2 ($ScCO_2$) instead of brine as a heat vector in Enhanced Geothermal Systems (EGS) to produce geothermal energy (generally electricity).
The concept requires deep drilling (generally 3-6 km), at least a doublet (1 injector & 1 producer), stimulation to increase permeability, then initialization of the system until CO_2 production.
For most conditions, energy efficiency is higher with CO_2 than with water/brine due to higher mobility and thermosiphon effect. Efficiency improvement around +50% could be expected.
High enthalpy CO_2 can be used either directly in a CO_2-compatible turbine or through a binary cycle with a heat exchanger. CO_2 is then cooled and compressed before reinjection.
Continuous external inflow of CO_2 is co-injected in order to compensate fluid loss in the reservoir (estimated around 5-10% of total flow). If CO_2 is contained at depth, it leads to significant amounts of CO_2 stored after 30 years of operation.

Services provided

- **Energy production**
  - 5 – 15 MWe
- **CO_2 storage**
  - 2 – 15 Mt CO_2 over 30 years
- Energy Storage Service



Index of services ratio
(defined with economic assumptions within the study)

Implementation complexity

2-5 deep wells

Stim.

Initialization (months)

Seismicity issue

Containment Sc CO_2

HEAT MINING WITH SUPERCRITICAL CO_2 IN DEPLETED OIL/GAS RESERVOIRS

2 - 4 km ~ **100 to 300°C**

External input
High during pressure recovery, then decreases to compensate loss

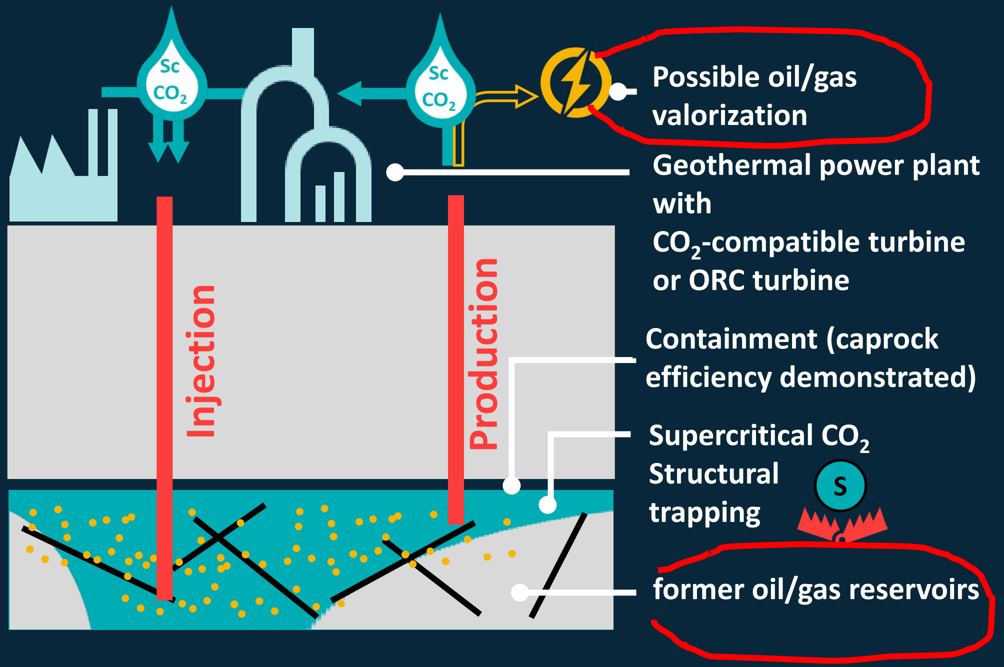
Supercritical CO_2
20-100 kg/s

loss

+
Combines non-intermittent renewable energy production and CO_2 storage
Limited costs (using/sharing already-existing data and infrastructure) and limited development risks
Containment already demonstrated

−
Replicability limited to former oil/gas reservoirs with suitable infrastructure.
Variable external CO_2 flow required

TRL
CO_2-EOR and CO_2-EGR already widely deployed
Hybridization with heat mining not yet demonstrated



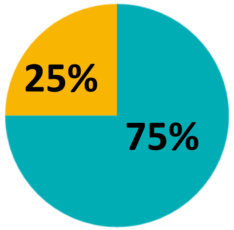
CO_2 has been widely used to assist/enhance production in CO_2 enhanced oil recovery (CO_2-EOR) and CO_2 enhanced gas recovery (CO_2-EGR). The addition of CO_2 increases the overall pressure of an oil/gas reservoir, and thus increases production.

Novel techniques have been proposed recently to push the concept forward and to use existing facilities at the end of oil/gas extraction in order to produce geothermal energy with supercritical CO_2 as a heat vector.
Different sequential exploitations might be possible. For instance, massive CO_2 injection might precede or follow the geothermal heat extraction.

Natural gas reservoirs are particularly suited for CO_2 storage due to self-proven sealing conditions of the natural gas. As an additional advantage, the available knowledge of geological conditions and the existing wells in the field facilitate implementation at lower cost than most other concepts.

SERVICES PROVIDED

- ENERGY PRODUCTION
  1 – 3 MWe
- CO_2 STORAGE
  2 – 16 Mt CO_2 over 30 years
- ENERGY STORAGE SERVICE



Index of services ratio
(defined with economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

Use/share existing infrastructure

CPG – ES (Energy Storage) or F (Flexible)

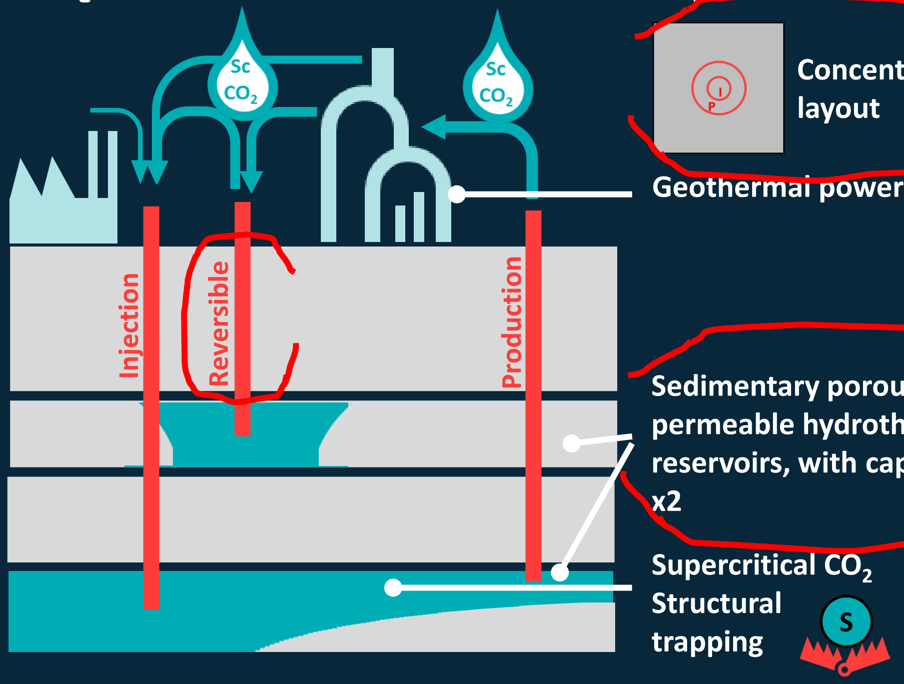
Deep: ~2.5 km
Shallow: 1-2km

Deep: ~100°C
Shallow: ~67°C

External input
5-30 kg/s

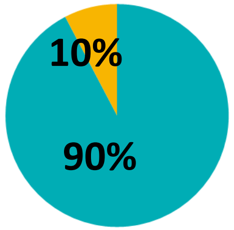
Supercritical CO_2
100-600 kg/s

5% loss



Services provided

- **Energy production**
  2.5 MWe
- **CO_2 storage**
  20 - 45 Mt CO_2 over 30 years
- **Energy storage service**
  Elasticity of exchanges with the electricity network:
  -15 MWe → +10 MWe



Index of services ratio
(defined with economic assumptions within the study)

+
Multi-services: CO_2 storage, base-load electricity production, electricity storage.
Outstanding performance
High flexibility between services

–
Requires 2 adequate aquifers, with tight caprocks. Limited replicability
Needs Initialization (around 2 years)
Complex system & complex integration
High investment costs
CO_2 containment and leakage risk issue

TRL
First paper in 2014
A few scientific articles.
Cradle: US

This concept is similar to CPG: supercritical CO_2 ($ScCO_2$) is used instead of brine as a heat vector in hydrothermal reservoirs (porous and permeable sedimentary formations) to produce geothermal energy (generally electricity), and to store CO_2.
In addition, it offers a flexible electricity storage service: the energy consuming part comes from CO_2 cooling and reinjection at depth. When the electricity demand is higher than the supply, CO_2 is exploited to produce electricity but is not reinjected at depth. Minimal parasitic load is used to inject CO_2 temporarily in a shallow aquifer. On the contrary, once the balance between electricity demand and supply reverses, electricity is retrieved from the grid to cool and inject CO_2 in the deep aquifer.
The concept requires drilling rings, a first one for injection and a second one for production, possibly with horizontal wells.
Continuous external inflow of CO_2 is co-injected in order to compensate fluid loss, it leads to a significant amount of CO_2 stored after 30 years of operation.

Implementation complexity

> 6 wells
Horizontal
2 aquifers

Initialization
(2 years)

Complex hybrid plant

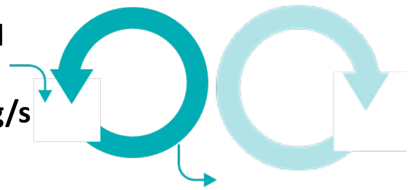
Integration in electricity network

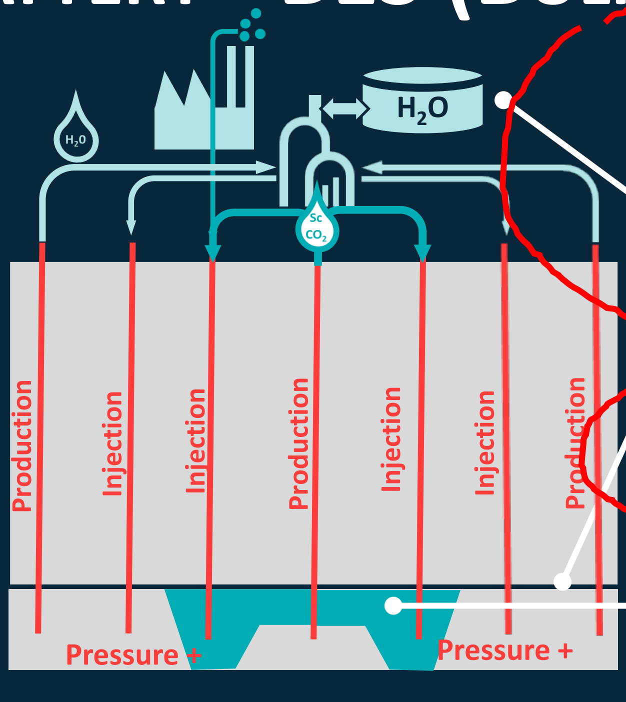
Containment Sc CO_2

Earth Battery - BES (Bulk Energy Storage)

3-5 km

130 - 200°C





Wells rings: concentric layout

Brine tank to store water and contribute to energy storage

Sedimentary porous and permeable reservoir with caprock

Supercritical CO_2 Structural trapping

+
Multi-services: CO_2 storage, base-load electricity production, electricity storage.
Outstanding performance
High flexibility between services
Pressure management limits leakage risks and increases efficiency

−
Very large scale, high investment costs
Complex system & complex integration
Surface storage required for brine

TRL
First paper in 2016
A few scientific articles.
Cradle: US

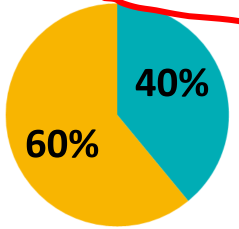
The concept combines: i. Geothermal energy exploitation (using brine and CO_2 as fluid vectors); ii. CO_2 storage; iii. Bulk energy storage (storage with high capacity) with a CO_2 pressurized cushion gas.
The concept relies on a much engineered reservoir management with different concentric rings. CO_2 from an external source is injected at the bottom of the second ring. Due to buoyancy effect, it migrates upward. Lateral migration is constrained by brine injection in the third ring that creates a pressure barrier. Thus the CO_2 is encapsulated in the central part below the impermeable caprock and creates a cushion gas cap that can be used for energy storage in the form of pressure. This pressure increase in the middle part of the system allows fluid production from ring 1 with limited pumping requirements (artesian flow). Fluid produced through ring 1 may consist of supercritical CO_2 and/or hot brine.
Brine is stored at the surface in tanks during unload (strong energy needs), and pressurized and injected during load phases. The possibility to time-shift these parasitic loads provides an energy storage service.

Services provided

Energy production
50-300 MWe

CO_2 storage
50-160 Mt CO_2 over 30 years

Energy Storage Service
Elasticity of exchanges with the electricity network:
-250 MWe → +500 MWe



Index of services ratio
(defined with economic assumptions within the study)

Implementation complexity

Tens of wells

Water tank

Complex system

Integration in electricity network

Containment Sc CO_2

CLASSIFICATION OF THE CONCEPTS

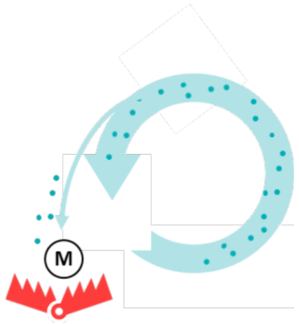
2.1

WATER-DRIVEN GEOTHERMAL HEAT EXTRACTION WITH CO_2 INJECTION TO ACHIEVE NEAR-ZERO CO_2 GEOTHERMAL PRODUCTION

CarbFix-like concept

0.7-2 km

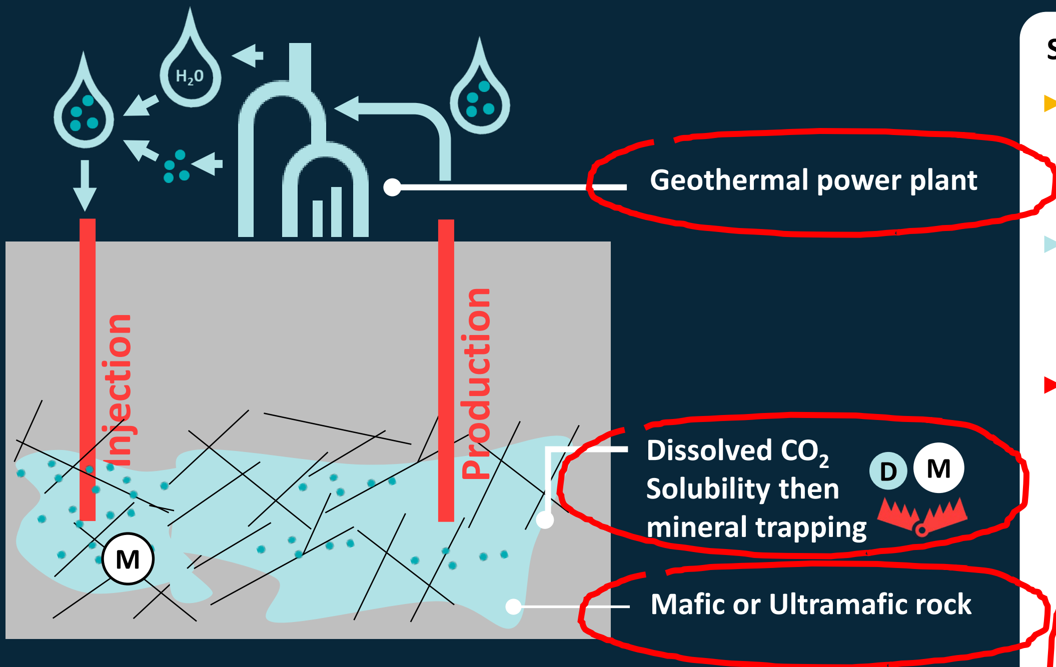
200 to 300°C



Water ~1000 kg/s with CO_2: 0.1% by mass (1kg/s)

→ CO_2 re-injected in dissolved form

Rapid mineral trapping



Large-size renewable energy production with limited emissions

Negligible risk of leakage

Replicability limited to specific geological context

No carbon storage from external source

Monitoring and management of Geochemical are challenges.

TRL

Pilot since 2011, demonstrator since 2014

Tens of papers, 2 on-going multi-partners projects in Europe.

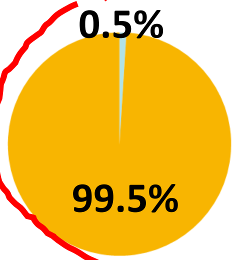
Cradle: Iceland

Recent new project in New Zealand

The CarbFix concept consists in injecting CO_2 into reactive rocks (such as mafic or ultramafic lithologies), provoking CO_2 mineralization and, thereby, permanently fixing carbon with negligible risk of return to the atmosphere.
In the Icelandic context, it is paired with geothermal heat extraction: the geothermal fluid used for electricity production at large scale (several hundreds of MWe) contains around 1% of CO_2 (mass ratio), as well as H_2S. CO_2 and H_2S are captured and reinjected in dissolved form in a distant well in order to achieve rapid mineralization at 0.7-2km depth.
The concept has been demonstrated at industrial scale since 2014 with promising results (majority of CO_2 is mineralized within 2 years). Risks and impacts have been thoroughly addressed and managed. Geochemical phenomena need to be well understood and quantified.
The replicability is limited to geological contexts with reactive rocks.
A variation of the concept has been proposed in New Zealand for less favorable geology, with ions injections to favor mineralization.

Services provided

- Energy production: ~300 MWe
- CO_2 avoided: 0.3 -1.2 Mt CO_2 over 30 years
- Energy Storage Service



Index of services ratio (defined with economic assumptions within the study)

Implementation complexity

- Tens of wells
- Geochemical management
- Seismicity issue

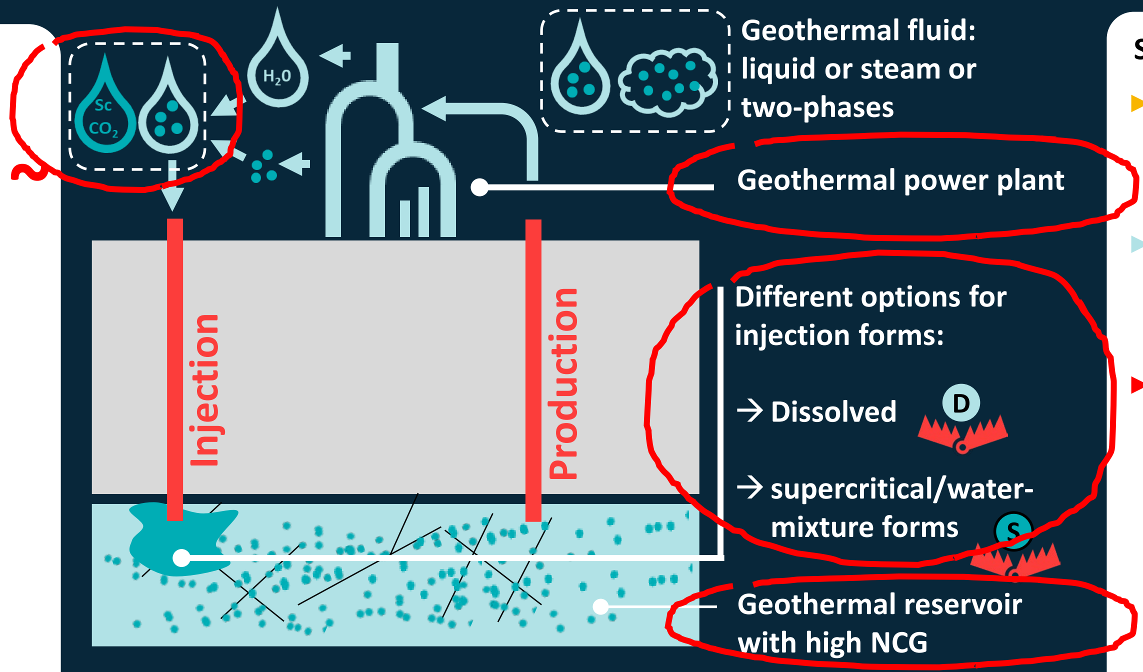
CO_2-REINJECTION CONCEPT – DISSOLVED OR SUPERCRITICAL

1.5-3.5 km

150 to 300°C

Water ~10-1000 kg/s with CO_2: 1-8% by mass

→ CO_2 re-injected in dissolved/supercritical/ water-mixture forms, depending on contexts



+ Large replicability potential, scalable concept
Large-size renewable energy production with limited emissions

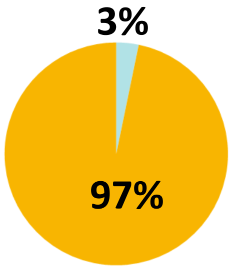
− No carbon storage from external source
Technical and containment challenges if injected in supercritical/ water-mixture forms

TRL Existing demonstrators (notably Kizildere in Turkey, Castelnuovo on stand-by in Italy)
Several papers, 2 on-going multi-partner projects in Europe.
Cradle: Europe (Turkey, Italy)

When operating a geothermal system, the native fluid pumped might contain non-condensable gases (NCG) such as CO_2, ammonia, nitrogen, methane, hydrogen sulphide, and hydrogen. Common practice is to release these gases to the atmosphere. Due to this, for a number of sites in Turkey and Italy, GHG emissions from geothermal power plants can be >500 g/kWh and, in some cases, greater than emissions from coal-fired power plants.
The present concept consists in capturing CO_2 emitted during geothermal exploitation (not from an outside emitter) to target near-zero emissions renewable energy production. CO_2 and other NCG are reinjected in dissolved form, or as a liquid-water mixture, or in supercritical form.
The deployment for the Turkish demonstrator (since 2022) and the Italian demonstrator (on stand-by) through the GECO and SUCCEED projects highlight highly variable plant sizes. Each configuration is unique with specific challenges.

SERVICES PROVIDED

- **Energy production**: 5 - 300 MWe ~
- **CO_2 avoided**: 0.3 -18 Mt CO_2 over 30 years ~
- **Energy storage service**



Index of services ratio
(defined with economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

Variable number of wells

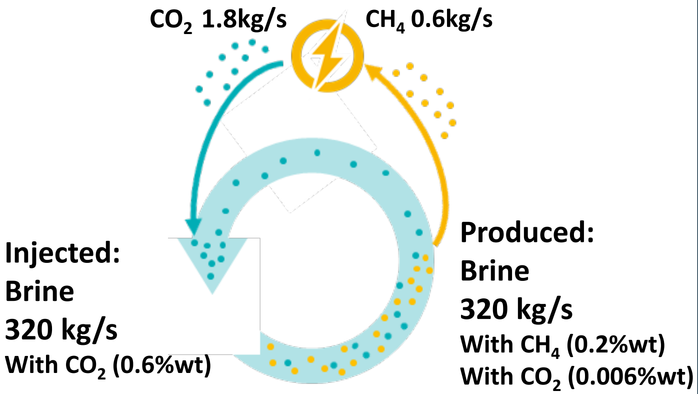
Geochemical management

Containment CO_2

CLEAG/AATG-LIKE CONCEPT

2 km

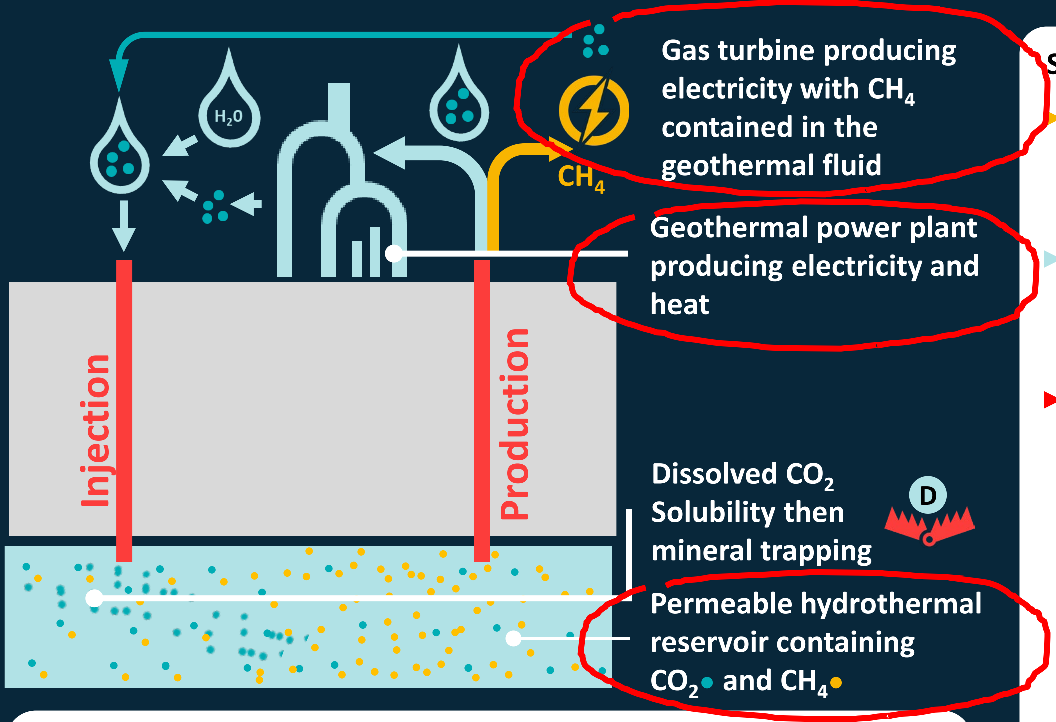
100 to 120°C



Outstanding performance by fully utilizing the geothermal hot brine content (heat and combustible gases) with near-zero emissions
Limited risks considering the dissolved form of CO_2
Plug&play modular design

Requires specific geological features, notably a significant methane content

TRL
A patent, but no scientific articles
Demonstrator in production since 2017
Already commercially self-sustaining
Cradle: Croatia



The concept consists in fully utilizing the energy potential of hot brines. It targets geothermal fluids that contain gases, between others combustible gases. In contrast to conventional geothermal power plants, CLEAG's hybrid system uses two sources for its energy production:

- Hot geothermal fluid (100-120°C) is used to generate electricity in an ORC turbine, and the remaining heat is used in a cascade for heat consumers in the near vicinity.
- Combustible gases dissolved in the geothermal fluid: gases are separated from water and used in gas engines for generation of electricity and heat in a combined heat and power (CHP) system.

CO_2 from the exhaust gases and native CO_2 are then reinjected in the geothermal reservoir at depth.
The demonstration project counts 4 production wells and 4 injection wells. The total energy capacity of the plant is 100 MW (80 MWth and 20 MWe, out of which the significant power consumption of the auxiliary equipment results in net generation of 12MWe).

SERVICES PROVIDED

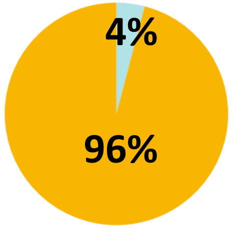
Energy production

12-20 MWe & 80MWth

CO_2 Avoided

1.7 Mt CO_2 over 30 years

Energy Storage Service



Index of services ratio
(defined with economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

A few wells

Geochemical management

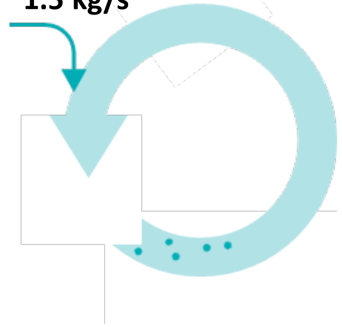
CLASSIFICATION OF THE CONCEPTS

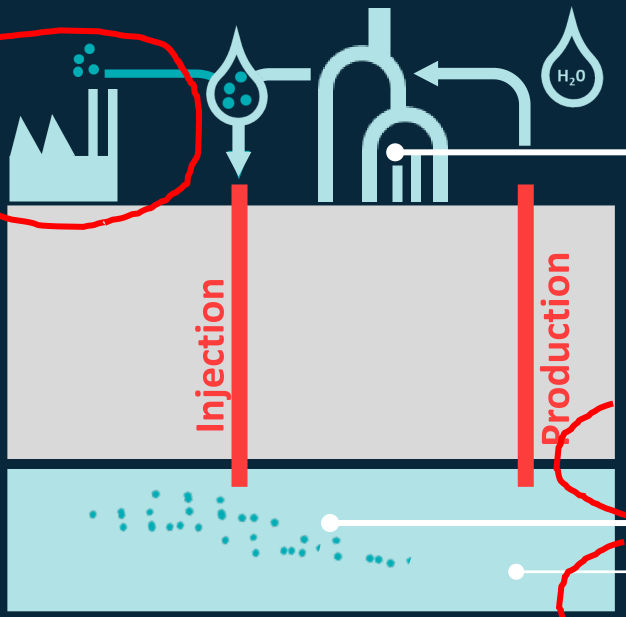
2.2

WATER-DRIVEN GEOTHERMAL HEAT EXTRACTION WITH INJECTION OF CO_2 IN THE DISSOLVED FORM FOR CCS

CO_2-DISSOLVED-LIKE CONCEPT

1.7 km | **60 to 80°C**





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- Outstanding performance by combining non-intermittent renewable heat production and CO_2 storage from an external emitter
- Large replicability potential
- Limited risks considering the dissolved form of CO_2

−

- Requires nearby a suitable formation, a heat user and a small CO_2 emitter
- Limited individual CCS potential

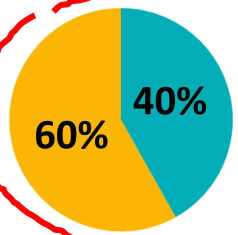
TRL

- First published in 2014
- Several scientific articles
- Pilot in planning in France
- Cradle: France

This concept consists in exploiting a conventional geothermal doublet with simultaneous CO_2 storage (from an external CO_2 emitter) in the form of CO_2 dissolved in the injected brine. It is adapted to smaller CO_2 industrial emitters (<150,000 t/year).
Water is pumped from a deep reservoir via a production well before being reinjected underground via a second injection well after dissolution of CO_2 captured at an industrial plant. The concept can work with any CO_2 capture technology, but the aqueous 'Pi-CO_2' (PI-Innovation, Inc., USA) techno is preferred as it produces carbonated water. CO_2 will reach the production well after some years (2 to 15 y); it is reinjected, but may limit the quantity of additional external CO_2 that can be dissolved if solubility limit is reached. The temperature target of the geothermal resource, in the range of 60-80°C, aims at producing heat and not electricity.
Ongoing work is aimed at preparing the first CO_2 injection tests in an existing geothermal doublet in the Paris basin, before moving to a demonstrator.

SERVICES PROVIDED

- ENERGY PRODUCTION: **4-6 MWth**
- CO_2 STORAGE: **1.2 Mt CO_2 over 30 years**
- ENERGY STORAGE SERVICE



Index of services ratio
(defined with economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

Doublet

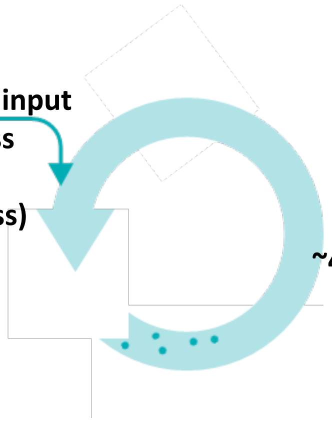
Geochemical management

GEOTHERMAL BECCS (BIOENERGY – CCS)

0.5-3 km

160°C

External CO_2 input
From biomass
~7-20 kg/s
(1.6% by mass)

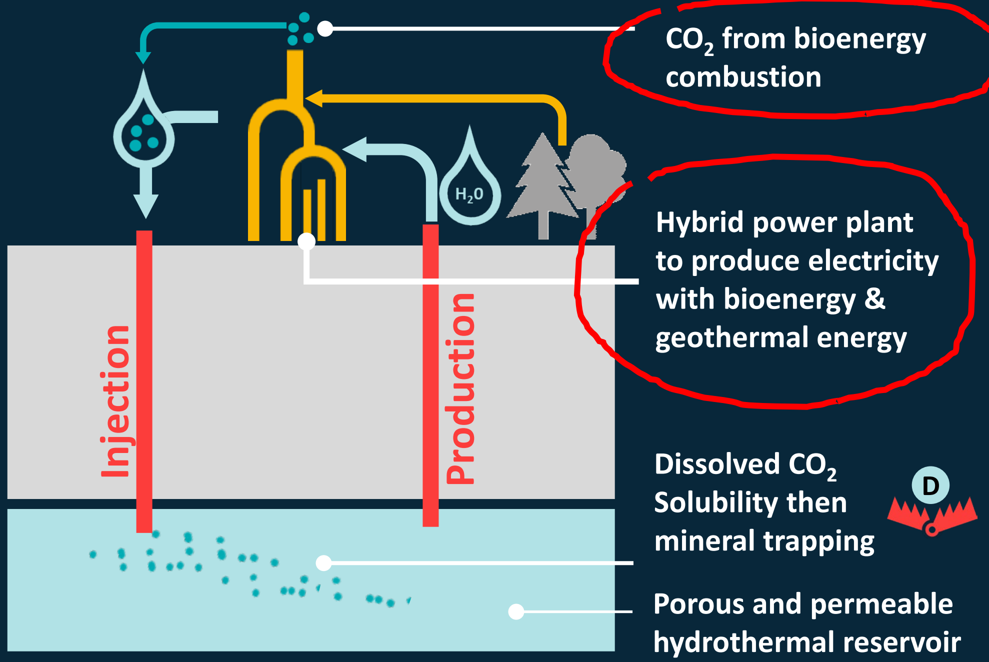


Geothermal fluid
~400-1200 kg/s

Outstanding LCA (negative emissions since stored CO_2 comes from biomass)
Large replicability potential
Limited risks considering the dissolved form of CO_2

Requires nearby a suitable formation and renewable biomass feeedsock
Complexity of design for the holistic system

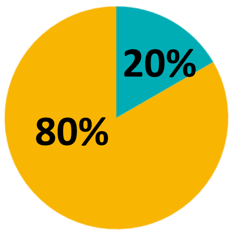
TRL
First published in 2022
1 article
Cradle: New Zealand



This concept called Geothermal-Bioenergy and Carbon Capture and Sequestration (Geothermal - BECCS) is a sub-concept of BECCS. It consists in using biomass as an energy resource, capturing CO_2 and storing it. The process is considered emission-negative since forests already remove CO_2 from the atmosphere as they grow.
The proposed hybridization with geothermal energy is the following: CO_2 is injected in dissolved form for CCS objective. A production well provides the water necessary for dissolution. A hybrid plant uses energy from geothermal fluid and from bioenergy to produce electricity with medium temperature geothermal resource (temperature not sufficient for efficient and economic electricity production in the absence of hybridization).
When using renewable bioenergy, the all system constitutes a carbon sink (between -200 and -700 gCO_2/kWh).
It was recently proposed in a scientific paper (Titus, 2022), but feasibility has not yet been demonstrated.

SERVICES PROVIDED

- ENERGY PRODUCTION
  - ~50 MWe*
  - *~100MWe for geothermal + bioenergy
- CO_2 STORAGE
  - ~10 Mt CO_2 over 30 years
- ENERGY STORAGE SERVICE



Index of services ratio
(defined with economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

At least a doublet

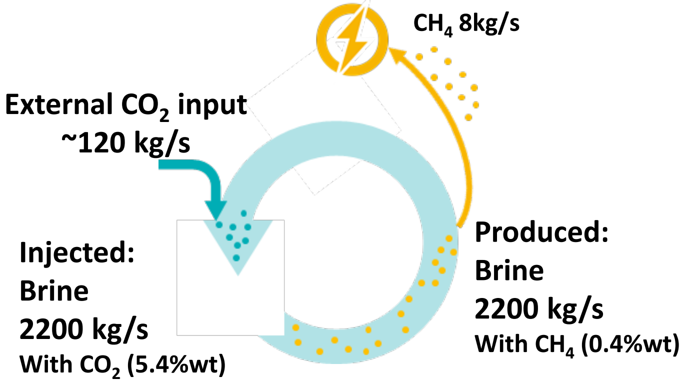
Geochemical management

Complex hybrid plant

CCS-DRIVEN CONCEPT (GEOTHERMAL ENERGY USED FOR CAPTURE AND FOR STORAGE IN DISSOLVED FORM)

3 km

150°C



+

Outstanding performance by fully utilizing the geothermal hot brine content (heat and combustible gases) to compensate energy required for carbon capture

Limited risks considering the dissolved form of CO_2

−

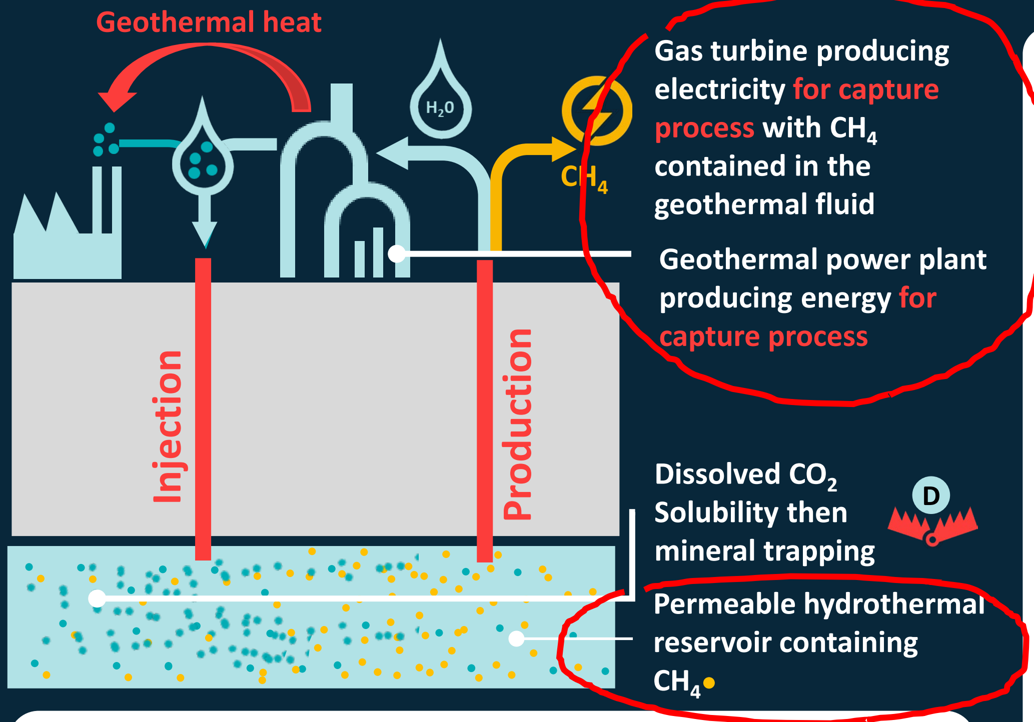
Requires specific geological features, notably a significant methane content

High investment costs

CO_2 breakthrough could be a hurdle

Feasibility debatable (huge volumes)

TRL 1 scientific article



The philosophy behind the concept is: "starting from CCS capture facilities, and considering the necessity of underground drilling, is it possible to improve the performance of the system with geothermal heat extraction in order to compensate additional energy required for capture?". The concept is driven by CCS, not by geothermal heat extraction.

It consists in fully utilizing the energy potential of hot brines. It targets geothermal fluids that contain methane, using:

- Hot geothermal fluid (100-120°C) (~250MWe)
- Combustible gases dissolved in the geothermal fluid to produce electricity (~500 MWth)

The sizing of the concept is designed to fulfil the CCS facility needs (15 injectors and 15 producers).

Authors show that brine production can yield methane and geothermal energy that slightly exceeds the energy required for capture and storage.

SERVICES PROVIDED

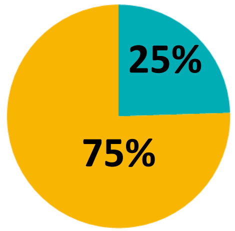
▶ ENERGY PRODUCTION

250 MWe & 500MWth

▶ CO_2 STORAGE

120 Mt CO_2 over 30 years

▶ ENERGY STORAGE SERVICE



Index of services ratio (defined with economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

Tens of wells

Geochemical management

CLASSIFICATION OF THE CONCEPTS

3

OTHER SYNERGIES (THE GEOTHERMAL FLUID AND CO_2 FOR CCS ARE HANDLED SEPARATELY)

SYNERGY THROUGH PRESSURE MANAGEMENT

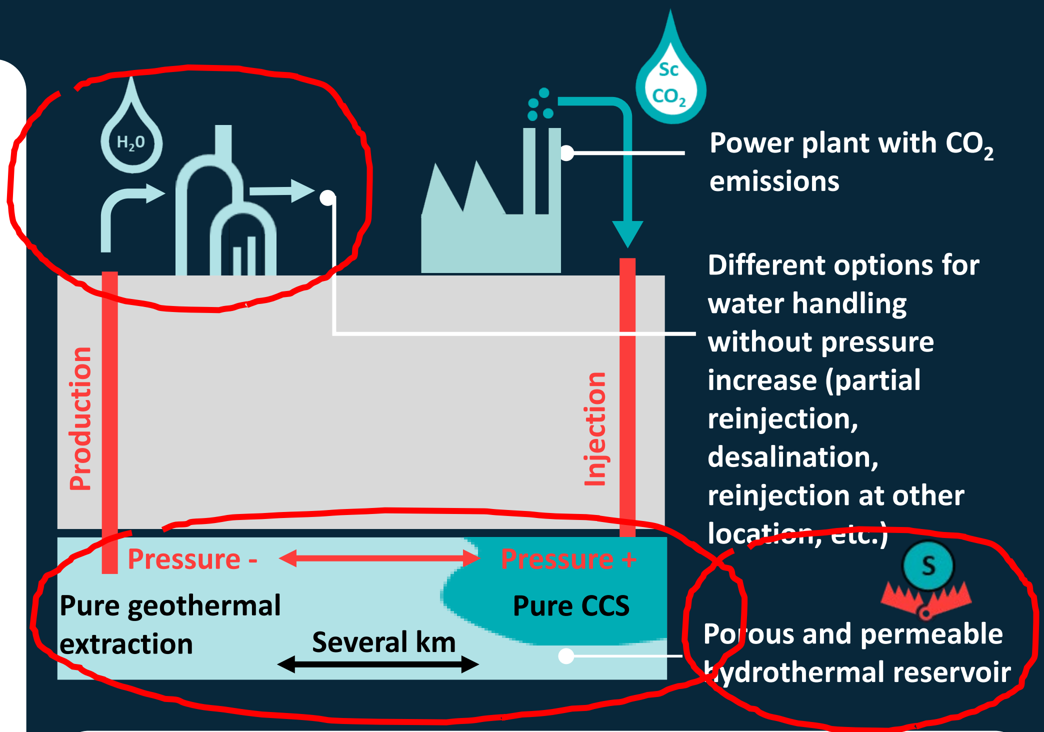
1-3 km

150°C

Brine for heat extraction ~50-250 kg/s

CO_2 ~100-500 kg/s for CCS

- - Pressure balance ++



For CCS, CO2 injection provokes pressure increase in the reservoir. It limits injectivity and storage capacity, and increases seismic and leakage risks. Therefore, solutions of Active CO2 Reservoir Management (ACRM) have been proposed by different authors to improve CCS performance.
They consist of withdrawing water from the storage reservoir. In order to make pressure decrease in the reservoir effective, a volume of brine equivalent to the volume of injected CO2 should be produced.
The extracted water can be used for geothermal heat/electricity production. In order to make pressure management effective, extracted water should not be (totally) reinjected in the reservoir. Different options could be studied: reinjection in seawater, reinjection in a shallower aquifer, reinjection at some distance, desalination, etc.
Nielsen et al. (2013) and Buscheck et al. (2013) showed that this concept limits pressure increase and increases CO2 storage capacity.

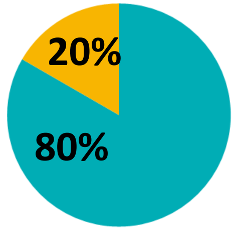
+ Outstanding performances by combining non-intermittent renewable energy production and CO2 storage from external emitter
High CO2 storage quantities
Sharing of data limits the costs.
Seismic risks reduced through pressure management.

– Underground system modeling and managing with both systems involves some complexity.
CO_2 confinement and risks/impacts issues

TRL Published in 2011
A few articles
Cradle: US, Norway, Danemark

SERVICES PROVIDED

- ENERGY PRODUCTION: ~50-500 MWth
- CO_2 STORAGE: ~100-500 Mt CO_2 over 30 years
- ENERGY STORAGE SERVICE



Index of services ratio
(defined with economical assumptions within the study)

IMPLEMENTATION COMPLEXITY

~2-10 wells

Complex reservoir management and modeling

Water handling

Confinement CO_2

SYNERGY THROUGH DUAL USE OF THE SAME RESERVOIR

~1 km

~50°C

Brine for heat extraction ~20 kg/s

CO_2 ~50 kg/s for CCS

+

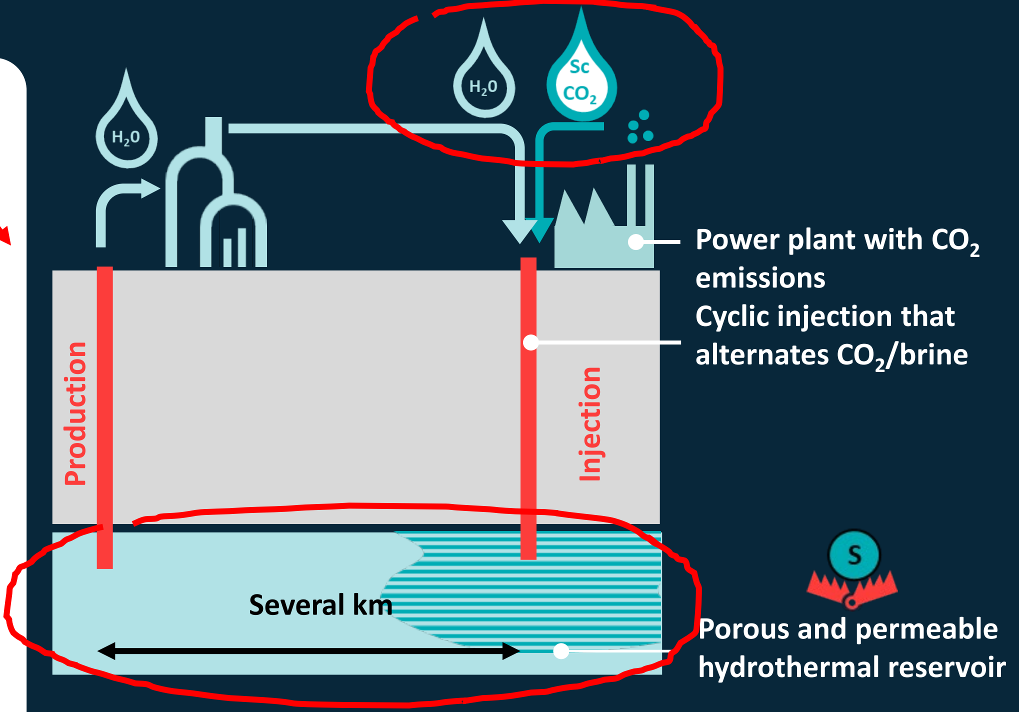
Outstanding performances by combining non-intermittent renewable energy production and CO2 storage from external emitter
High CO2 storage quantities
Sharing of data and of injection well limits the costs.

−

Underground system modeling and managing with both systems involves some complexity.
CO_2 confinement and risks/impacts issues

TRL

Published in 2013
1 article
Cradle: Germany



Power plant with CO_2 emissions

Cyclic injection that alternates CO_2/brine

Porous and permeable hydrothermal reservoir

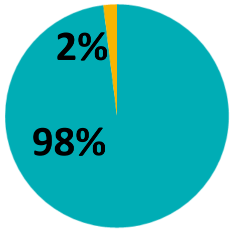
In this concept, the same reservoir is used for both CCS and geothermal heat mining. It allows synergies for the exploration phase, data acquisition, and for some infrastructures.

In the case study proposed by Tillner et al. (2013) in Germany, geothermal heat mining and CCS are located at a distance of 7 km. A production well is used for geothermal brine production. A unique injection well is used for both CO2 injection and brine reinjection.

Their results demonstrate that the competitive character between both technologies can be neglected and that a synergetic reservoir utilization can be realized in the chosen study area.

SERVICES PROVIDED

- ENERGY PRODUCTION
  ~2 MWth (?)
- CO_2 STORAGE
  ~50 Mt CO_2 over 30 years
- ENERGY STORAGE SERVICE



Index of services ratio
(defined with economical assumptions within the study)

IMPLEMENTATION COMPLEXITY

~2 wells

Complex reservoir management and modeling, injection cycles

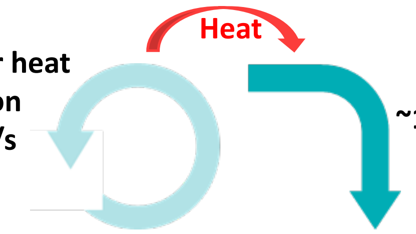
Sc CO_2

Confinement CO_2

Hybrid Energy System

1-2 km ~

90-200°C ~



+

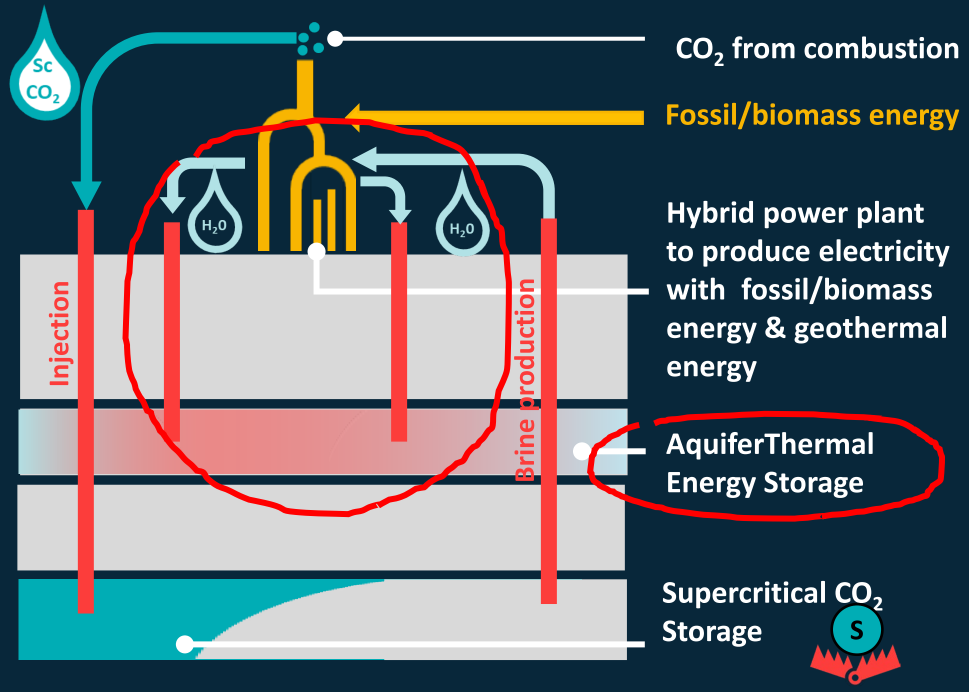
Optimisation of energy performance (geothermal energy used for pre-heating)
Multi-services: CO_2 storage, base-load electricity production, energy storage.
High CO_2 storage quantities

−

Requires two suitable reservoirs for both uses
High investment costs (two independent systems with limited synergy)
High complexity and large-scale

TRL

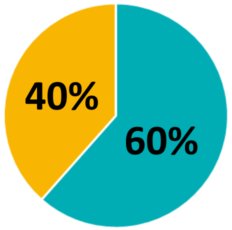
Published in 2021
1 article, patented
Cradle: US



This hybrid-approach produces electricity with near-zero carbon emission (or even negative emissions if biomass is used). Variable renewable energy, geothermal energy, and fossil energy with CCS are integrated in a single facility, which significantly improves the use of all energy sources. Geothermal energy is used to pre-heat the fluid before combustion. Consequently, high temperatures are reached, with limited use of fossil resources, and with high conversion efficiency.
In order to optimise the carbon capture and storage process, CO2 is produced with high purity, relying on combustion with pure oxygen (oxy-combustion).
For a 550 MWe power plant, geothermal energy supplies 21-75 MWe. CO_2 is stored in supercritical form. Pressure reservoir management is proposed to increase performance and safety. Extracted brine is used for geothermal energy production. It is reinjected after heat extraction, partly in a shallower aquifer. This shallower aquifer is also used for thermal energy storage.

Services provided

- **Energy production**
  - ~21-75 MWe*
  - *the production of electricity associated with geothermal heat in a 550 MWe power plant
- **CO_2 storage**
  - ~50-100 Mt CO_2 over 30 years ~
- **Energy storage service**
  - Short-term and seasonal storage



Index of services ratio (defined with economic assumptions within the study)

Implementation complexity

~Tens of wells

Complexity (2 reservoirs with service articulation)

Integration in electricity network for storage

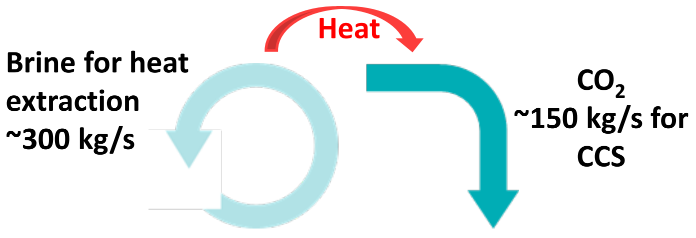
? Water not entirely reinjected (should be managed)

Containment CO_2

CCS WITH GEOTHERMAL ENERGY FOR CAPTURE PROCESS

1.5-2 km ~

150°C ~



+

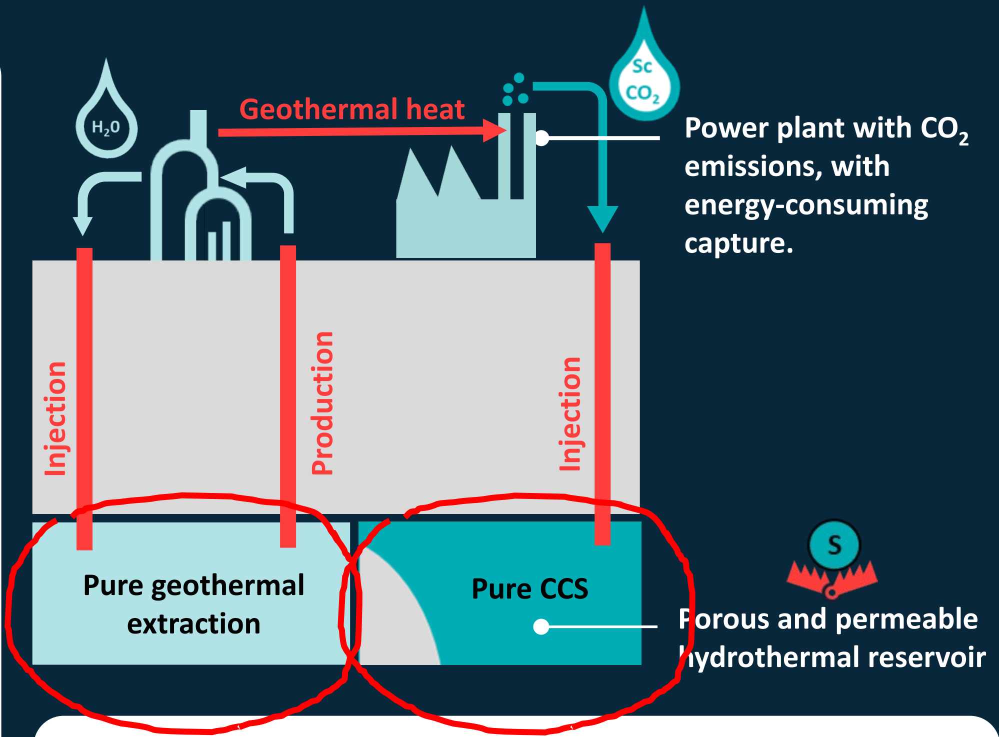
Improvement of CCS environmental benefits.
High CO2 storage quantities.
Limited temperature required for geothermal brine.

−

Requires two suitable reservoirs for both uses
High investment costs (two independent systems with limited synergy)
CO_2 confinement and risks/impacts issues

TRL

Published in 2017 (Davidson et al.)
1 article
Cradle: US



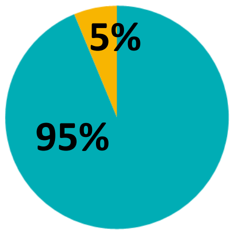
The main objective remains the storage of CO_2. When analyzing the whole chain, the authors pointed out that the energy consumed for the process of CO2 capture represents a non-negligible penalty for carbon reduction. In order to improve the benefit of CO_2 storage, the authors investigated the potential to use geothermal energy to provide boiler feedwater preheating. The theoretical results of this study indicate promising results of using geothermal energy to increase the benefits of CCS with power load associated with capture that could be offset by roughly 7%.

With the same coal consumption, using geothermal energy allows earning 10 MWe for a 550 MWe power plant.

The subsequent storage of CO_2 is not addressed in the study.

SERVICES PROVIDED

- **ENERGY PRODUCTION**
  - ~10 MWe*
  - *the capcaity of the power plant increases of 10MWe for a 550 Mwe coal-fired power plant
- **CO_2 STORAGE** ~
  - ~150 Mt CO_2 over 30 years
- ENERGY STORAGE SERVICE



Index of services ratio
(defined with economical assumptions within the study)

IMPLEMENTATION COMPLEXITY

~5 wells

Complexity (2 reservoirs with service articulation)

Confinement CO_2

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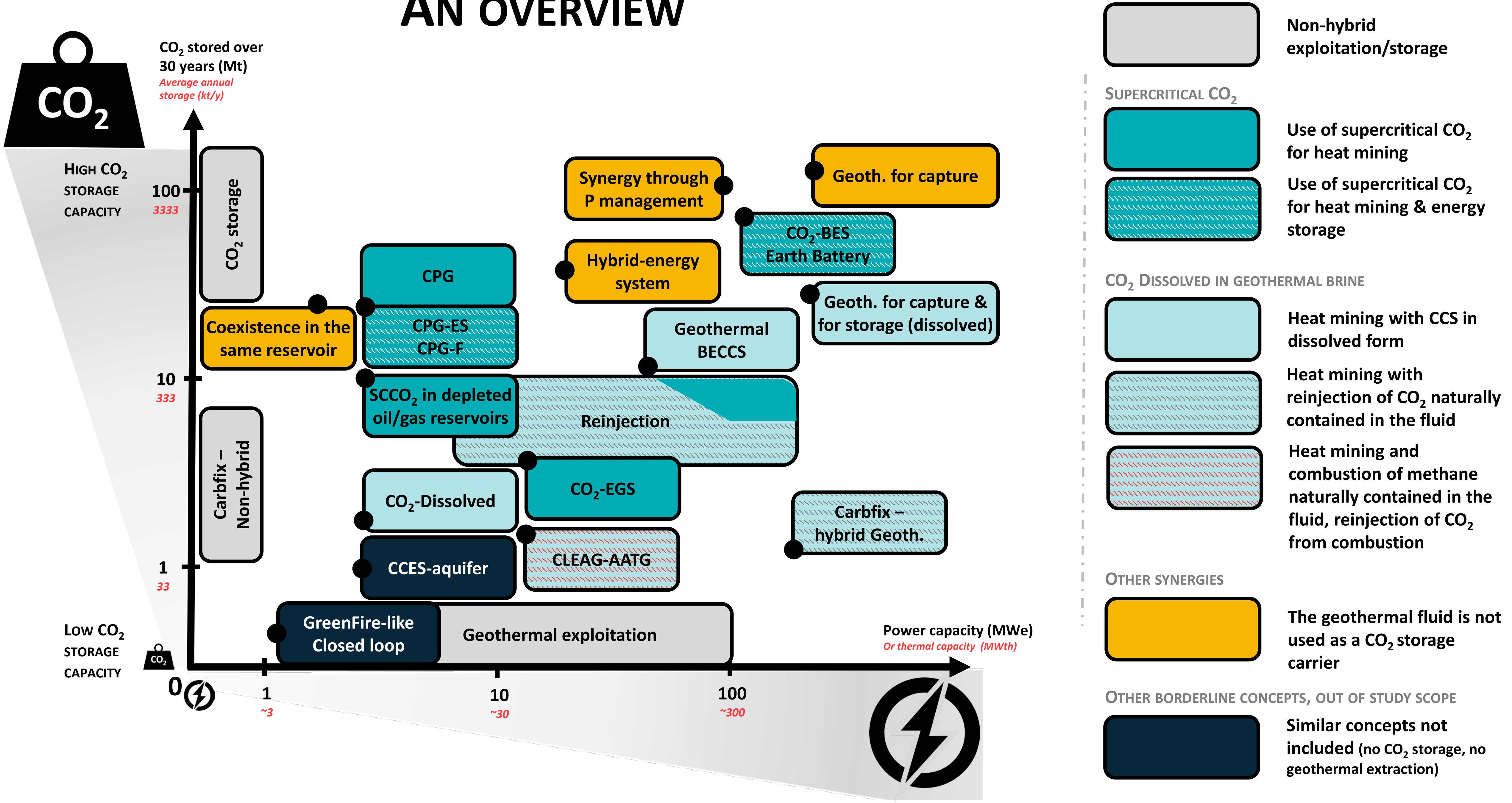
SCREENING METHODOLOGY AND ANALYSIS GRID OF COMBINED CCS/GEOTHERMAL PROJECTS

Screening methodology and analysis grid

Infographics

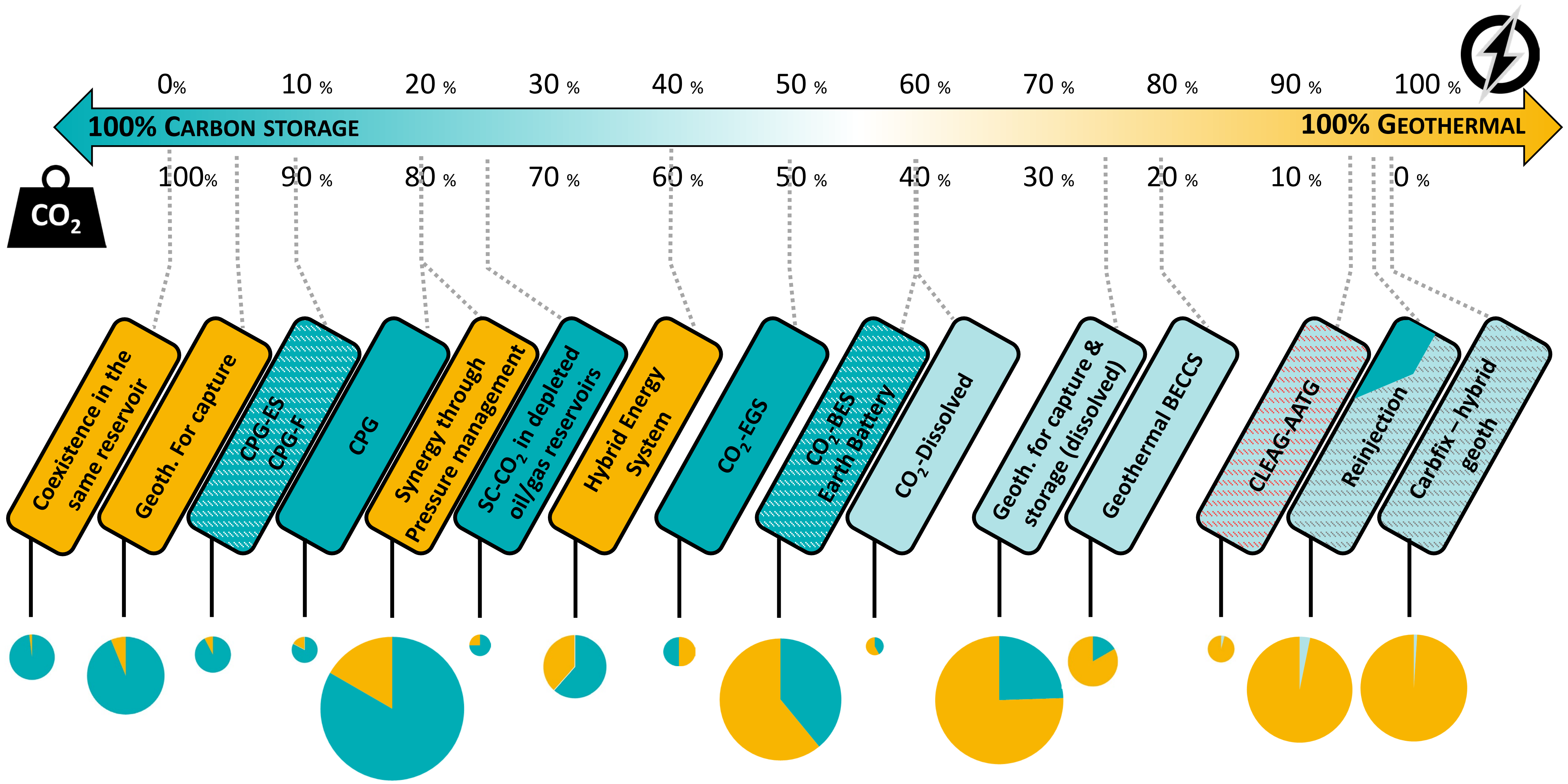
Comparison based on criteria

AN OVERVIEW

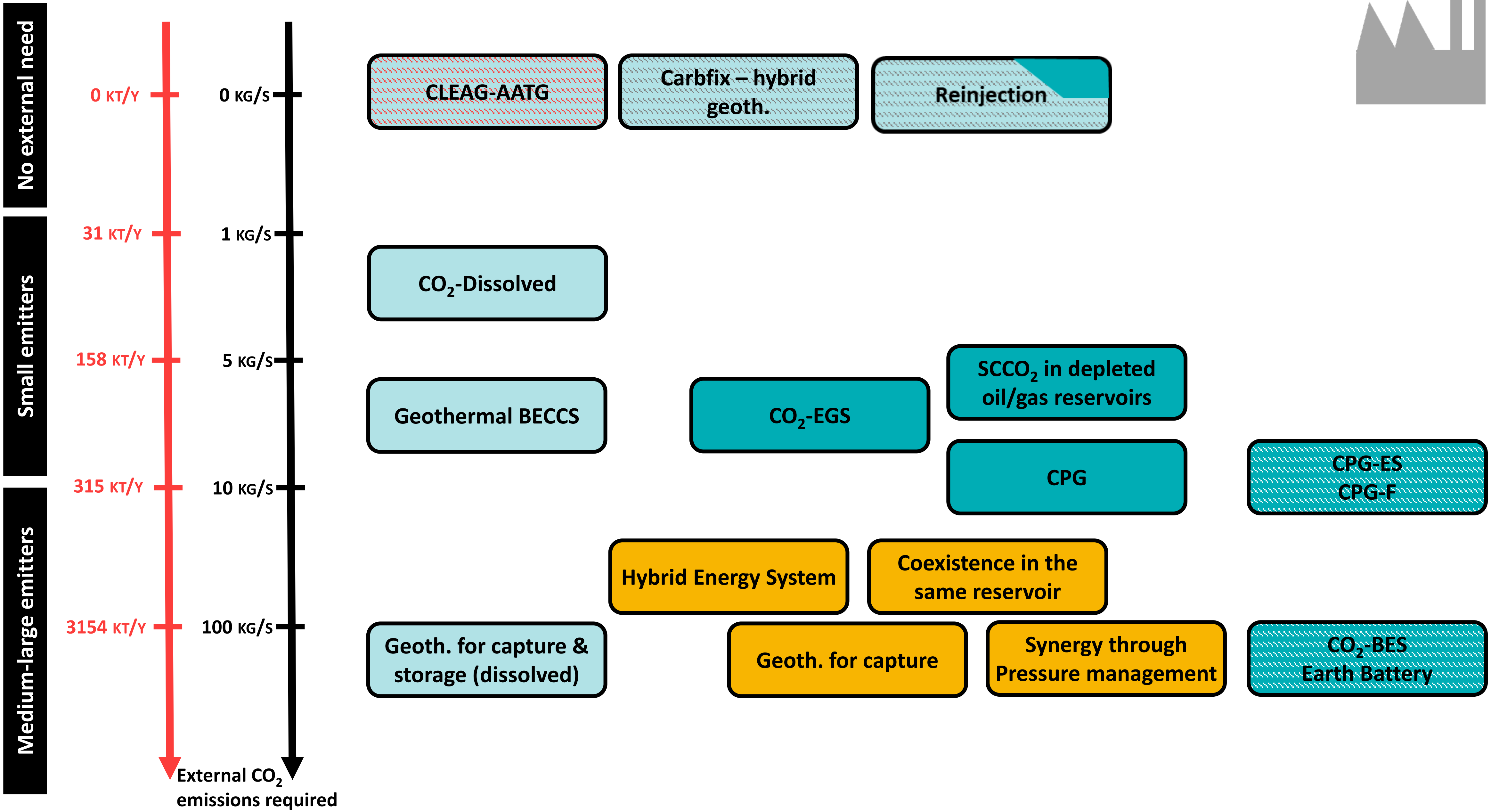


CO_2
CO_2 stored over 30 years (Mt)
Average annual storage (kt/y)
HIGH CO_2 STORAGE CAPACITY
LOW CO_2 STORAGE CAPACITY
100
3333
10
333
1
33
0
1
~3
10
~30
100
~300
Power capacity (MWe)
Or thermal capacity (MWth)
CO_2 storage
Carbfix – Non-hybrid
Coexistence in the same reservoir
CPG
CPG-ES
CPG-F
$SCCO_2$ in depleted oil/gas reservoirs
Reinjection
CO_2-Dissolved
CO_2-EGS
CCES-aquifer
CLEAG-AATG
GreenFire-like Closed loop
Geothermal exploitation
Synergy through P management
Hybrid-energy system
Geothermal BECCS
Geoth. for capture
CO_2-BES Earth Battery
Geoth. for capture & for storage (dissolved)
Carbfix – hybrid Geoth.
Non-hybrid exploitation/storage
SUPERCRITICAL CO_2
Use of supercritical CO_2 for heat mining
Use of supercritical CO_2 for heat mining & energy storage
CO_2 DISSOLVED IN GEOTHERMAL BRINE
Heat mining with CCS in dissolved form
Heat mining with reinjection of CO_2 naturally contained in the fluid
Heat mining and combustion of methane naturally contained in the fluid, reinjection of CO_2 from combustion
OTHER SYNERGIES
The geothermal fluid is not used as a CO_2 storage carrier
OTHER BORDERLINE CONCEPTS, OUT OF STUDY SCOPE
Similar concepts not included (no CO_2 storage, no geothermal extraction)

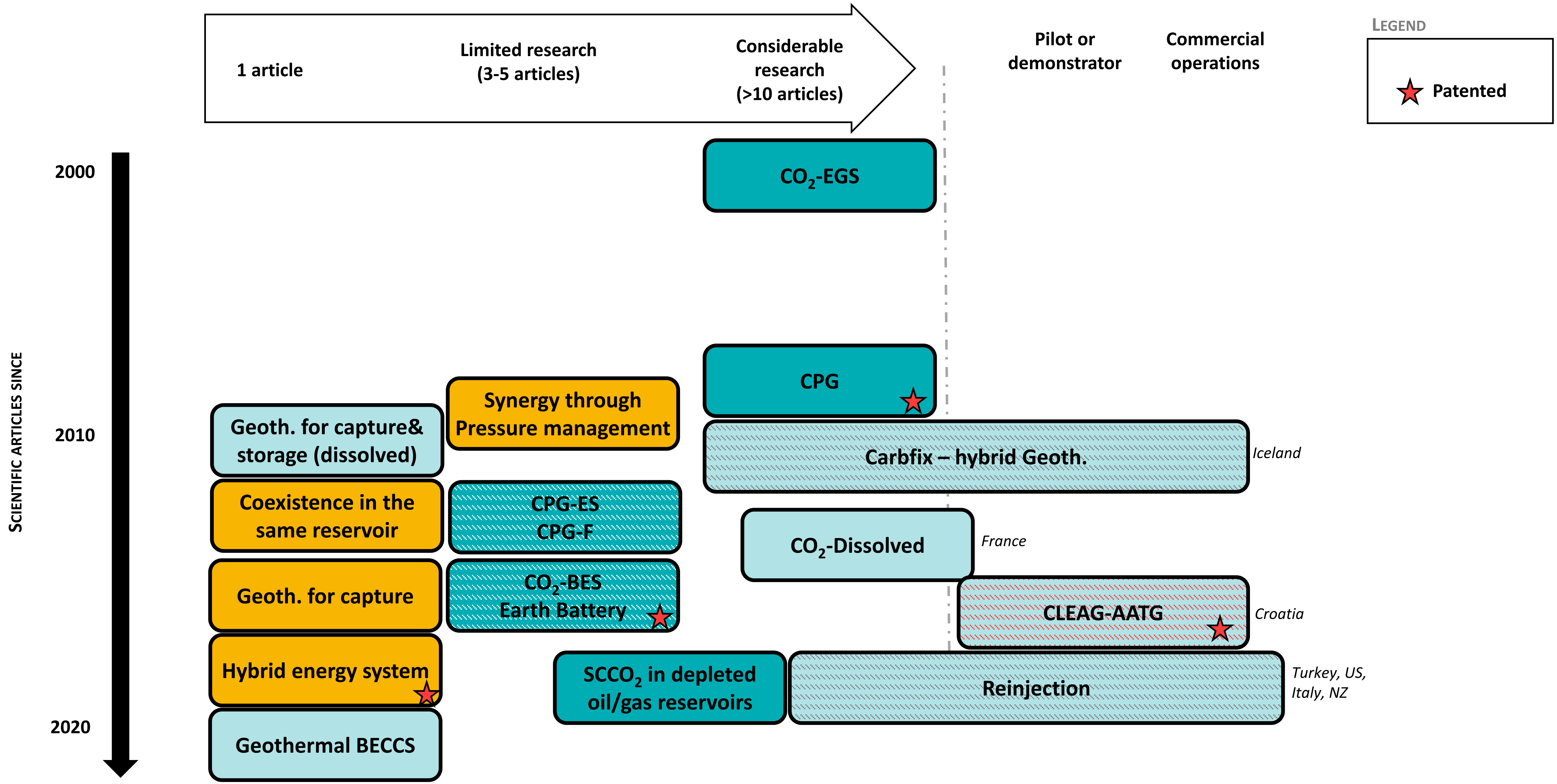
Comparison of concepts on the CCS – geothermal energy scale



VIEWPOINT OF EXTERNAL EMITTERS



OVERVIEW OF RESEARCH AND PATH TO COMMERCIALITY



Screening methodology and analysis grid

Infographics

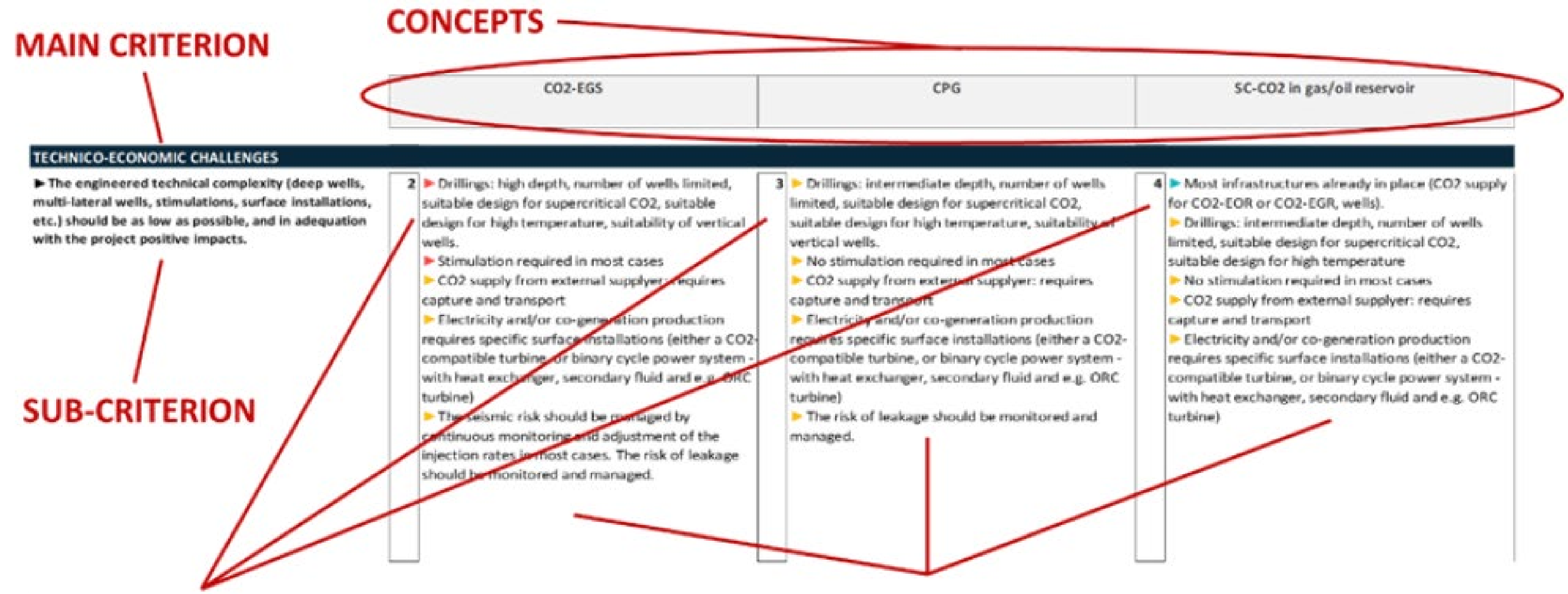
Comparison based on criteria

Key Performance Indicators (KPIs)

17 KPIs grouped into 7 categories:

- Provide qualitative criteria
- Attempt to quantify the performance for each of the 17 criteria (a score between 1 and 5 is proposed)
- A total score, obtained by summing all score per criterion, is not proposed as it is meaningless as only a weighted average could make sense (and this is not a neutral approach, by definition).
- All data are included in an Excel spreadsheet attached to the report that the reader can manipulate and then run their own performance calculations according to their own specific priorities.

KEY PERFORMANCE INDICATORS (KPIs)



NOTATION ON A 1-5 SCALE

QUALITATIVE ARGUMENTS:

- turquoise: favourable argument
- Yellow: neutral/nuanced argument
- Red: Not favourable argument

KEY PERFORMANCE INDICATORS (KPIs)

Example of global scores (1-5) per KPI category for all the concepts:

	AMBITIONS & REPLICABILITY	INTEGRATION, MODULARITY & SCALABILITY	PERCEPTION BY STAKEHOLDERS	READINESS	ENVIRONMENTAL RISKS & IMPACTS	TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	CREDIBLE PATH TO COMMERCIALITY
CO2-EGS	3.3	3.3	2.0	2.0	3.0	1.0	1.5
CPG	4.3	3.0	3.0	3.0	3.8	3.0	3.0
Heat mining with SC-CO2 in gas/oil reservoir	2.5	4.0	4.0	4.0	4.3	3.0	4.5
CPG-ES	3.8	2.7	3.0	2.0	3.5	2.5	2.0
Earth Battery - CO2-BES/TES	4.5	3.0	3.0	2.0	3.5	2.5	2.5
Carbfix*-like concept	2.5	4.3	5.0	5.0	4.3	4.0	4.0
CO2-reinjection concept	3.5	3.7	4.0	3.0	4.3	3.5	3.0
CLEAG-like concept	3.0	4.0	5.0	5.0	4.3	4.5	4.0
CO2-Dissolved-like concept	4.0	4.0	3.0	4.0	4.3	4.5	4.0
Geothermal BECCS	4.8	4.3	3.0	3.0	4.0	3.5	4.0
CCS-driven concept	2.8	3.7	3.0	2.0	4.0	3.5	2.5
CCS with geothermal energy for capture process	3.3	3.7	3.0	3.0	3.8	3.5	3.5
Hybrid-energy systems	3.5	4.0	3.0	2.0	3.8	3.5	3.0
Synergetic use through dual uses in the same reservoir	4.0	3.3	3.0	3.0	3.8	3.0	4.0
Synergy through pressure management	4.3	3.0	3.0	4.0	4.0	3.5	4.0

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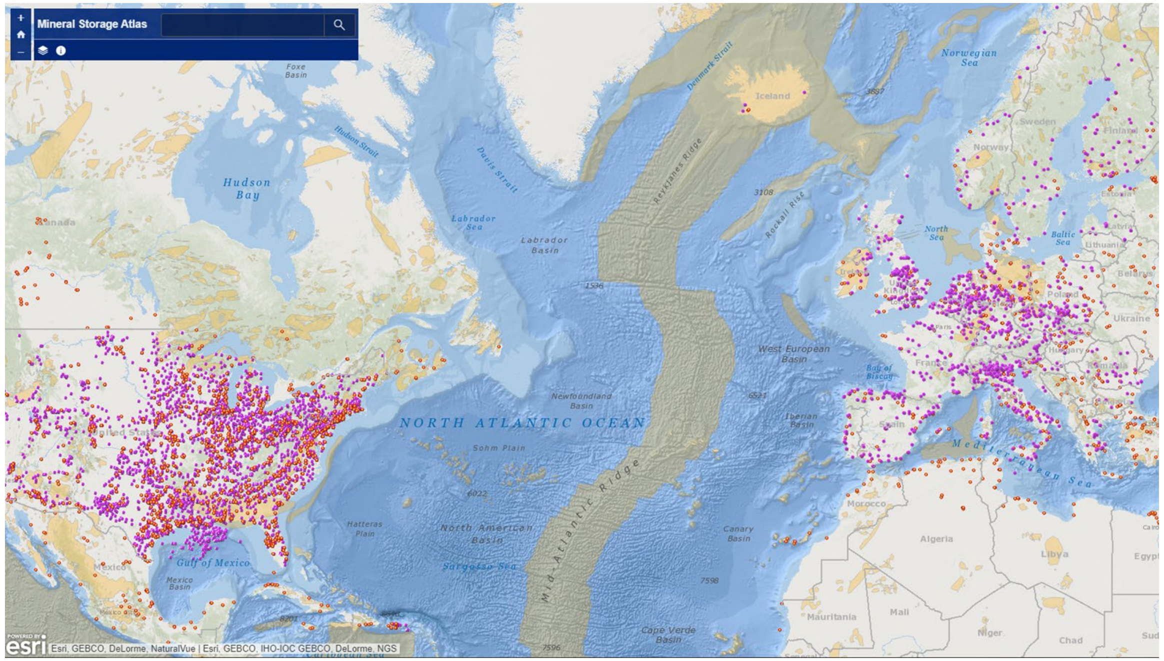
ASSESSMENT OF POTENTIAL APPLICATION AREAS FOR COMBINED CCS/GEOTHERMAL PROJECTS

BASIC METHODOLOGY

- Each concept requires the coexistence of:
  - ✓ Favourable geological conditions for geothermal exploitation and safe CO_2 storage
  - ✓ If the CO_2 source is distant, a CO_2 source or a transport infrastructure as close as possible to the site

- Produce geological maps + CO_2 source/network maps and superimpose the two maps to identify the most favourable areas, ideally at world, country, and/or regional scales.



Example of the Carbfix atlas

Favourable geology

CO_2 sources

Power plants

BUT REALITY IS MORE COMPLEX…

- These appropriate geological and CO_2 source maps are not available for every country and generally have to be built from raw data… when these data are available.

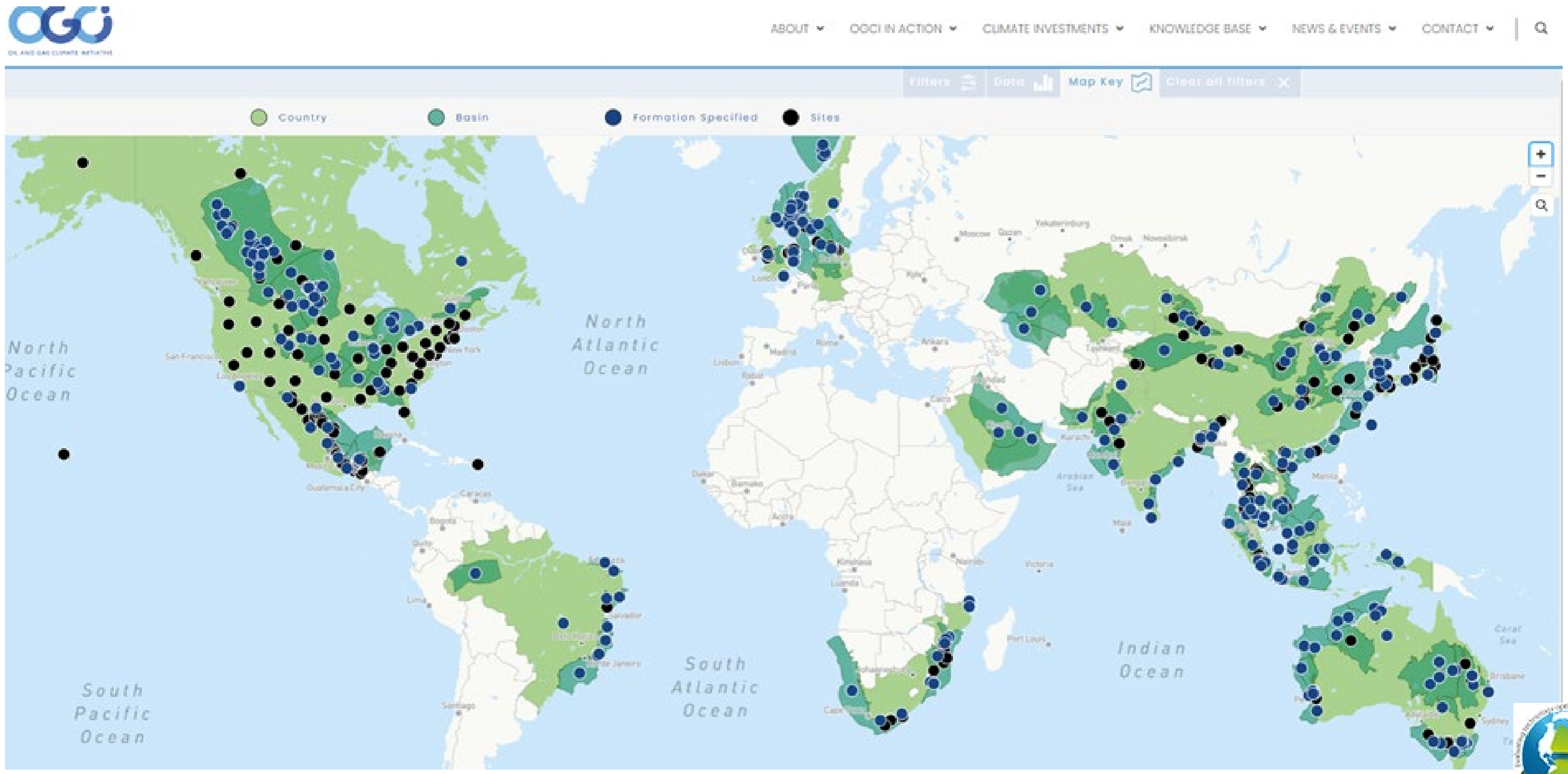
- The above-mentioned criteria alone do not guarantee the applicability of a concept. Apart from technical and scientific questions, the following criteria need be considered, such as the existence of:
  - ✓ land availability close to the pre-identified site
  - ✓ a local interest for exploiting geothermal heat/electricity
  - ✓ a nearby heating network
  - ✓ local plans to develop an activity requiring heat and/or electricity
  - ✓ ease of connection to the grid and/or local use of electricity
  - ✓ local social and political acceptance for the project
  - ✓ a carbon tax legislation (local, national, international)
  - ✓ a sound business model (more complex to establish for these types of hybrid activities)

SO WHAT…?

- It was not possible to produce specific maps for all the concepts presented at the various scales to have a first screening view on their applicability.
- We have provided exemplary case studies to illustrate what could be achievable in a future dedicated mapping project

SUBSURFACE DATA IN ORDER TO IDENTIFY AND CHARACTERIZE APPROPRIATE RESERVOIRS

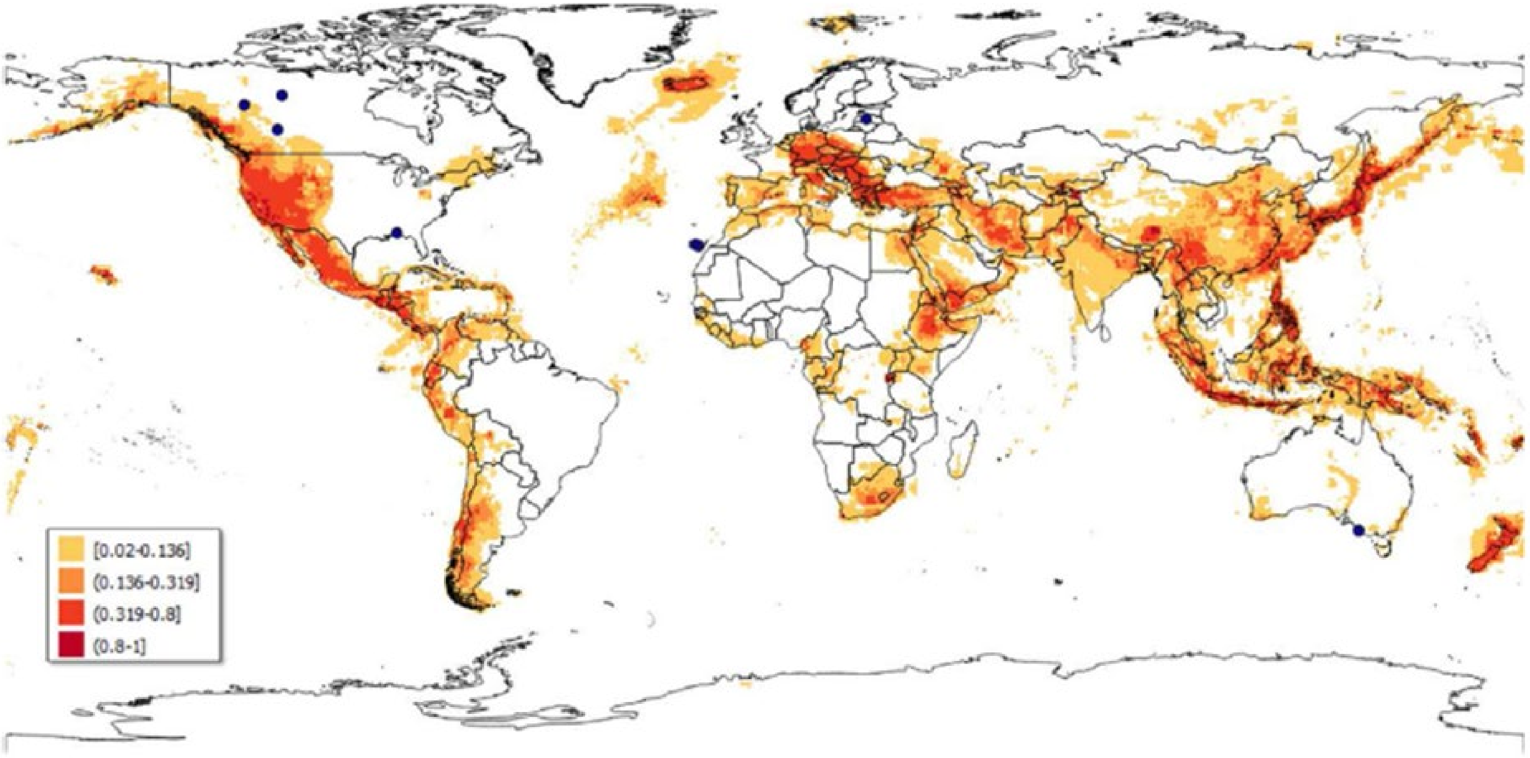
- For CCS:



Example of the OGCI's CO_2 storage catalogue map

SUBSURFACE DATA IN ORDER TO IDENTIFY AND CHARACTERIZE APPROPRIATE RESERVOIRS

- For geothermal energy (at world, continent, country/state/region scales):



Example of computed geographical suitability of geothermal power plants at the world scale (*Coro and Trumpy, 2020*).

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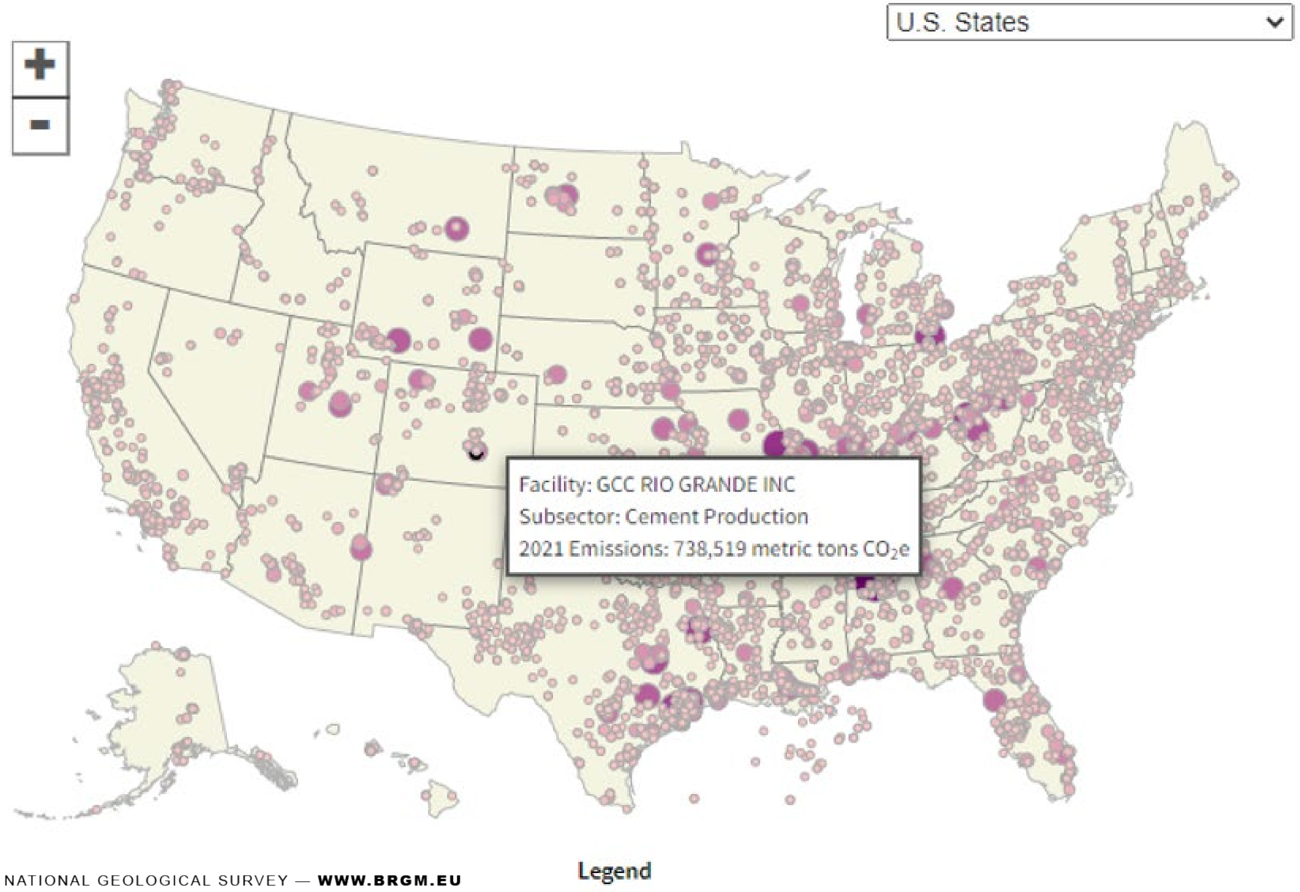
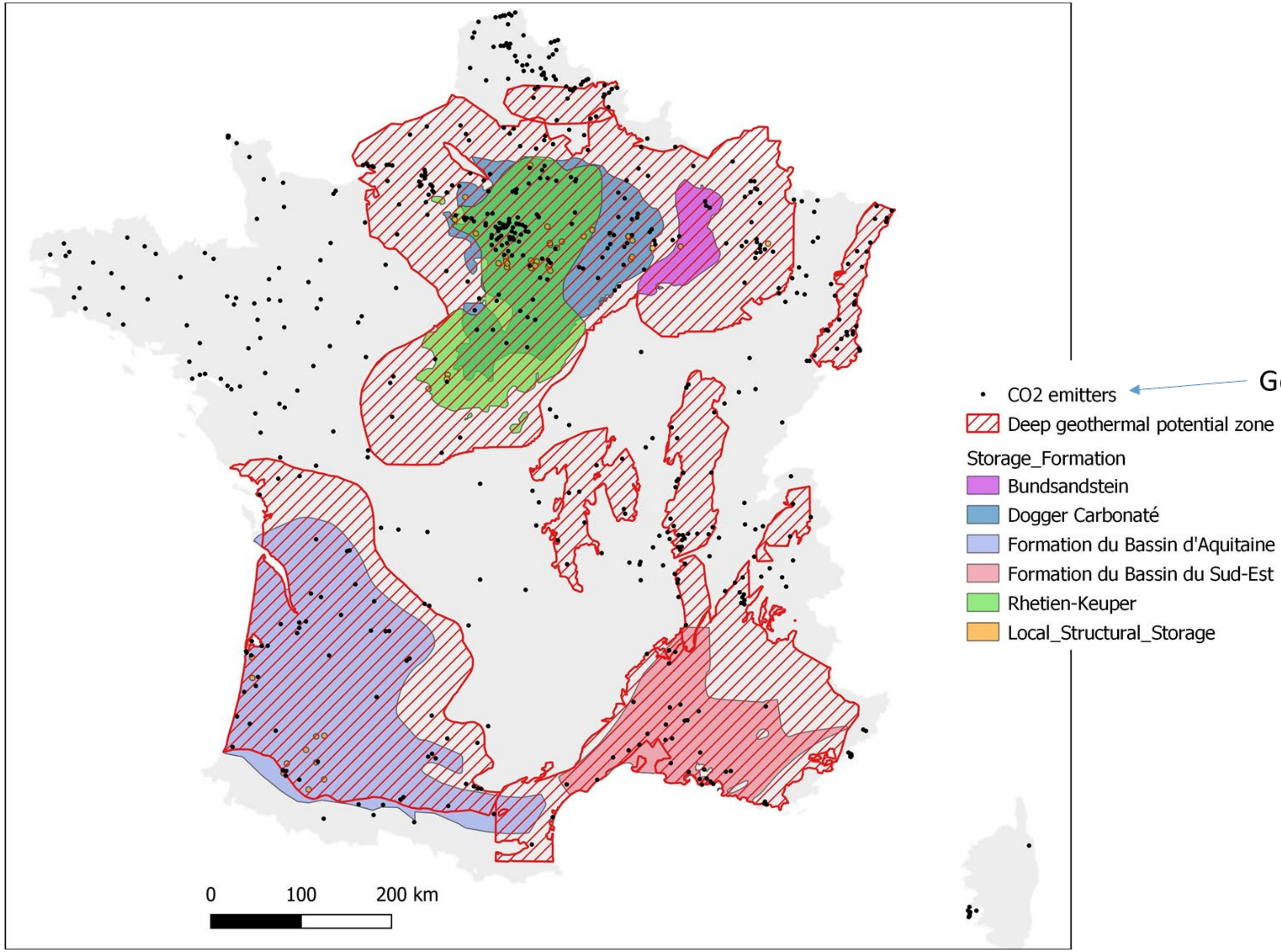
DATA ON INDUSTRIAL CO_2 EMISSIONS

- At world, continent, country/state/region scales:



Example of the interactive map of the US industrial CO_2 emitters (available on the US-EPA website)

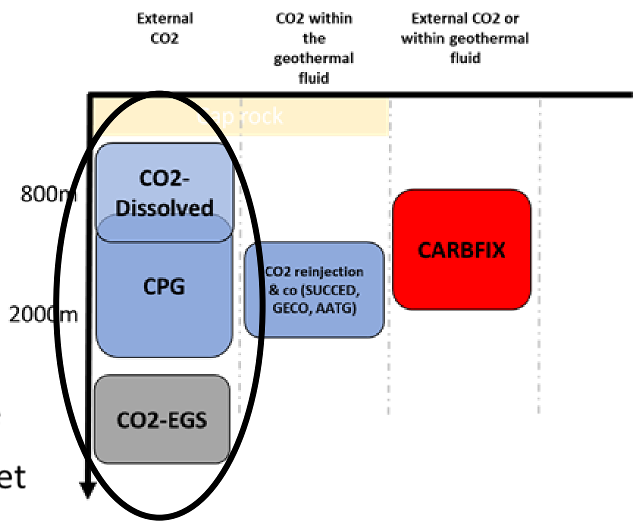
COMBINING DATA TO ASSESS FAVOURABLE AREAS FOR COMBINED GEOTHERMAL ENERGY PRODUCTION AND CCS



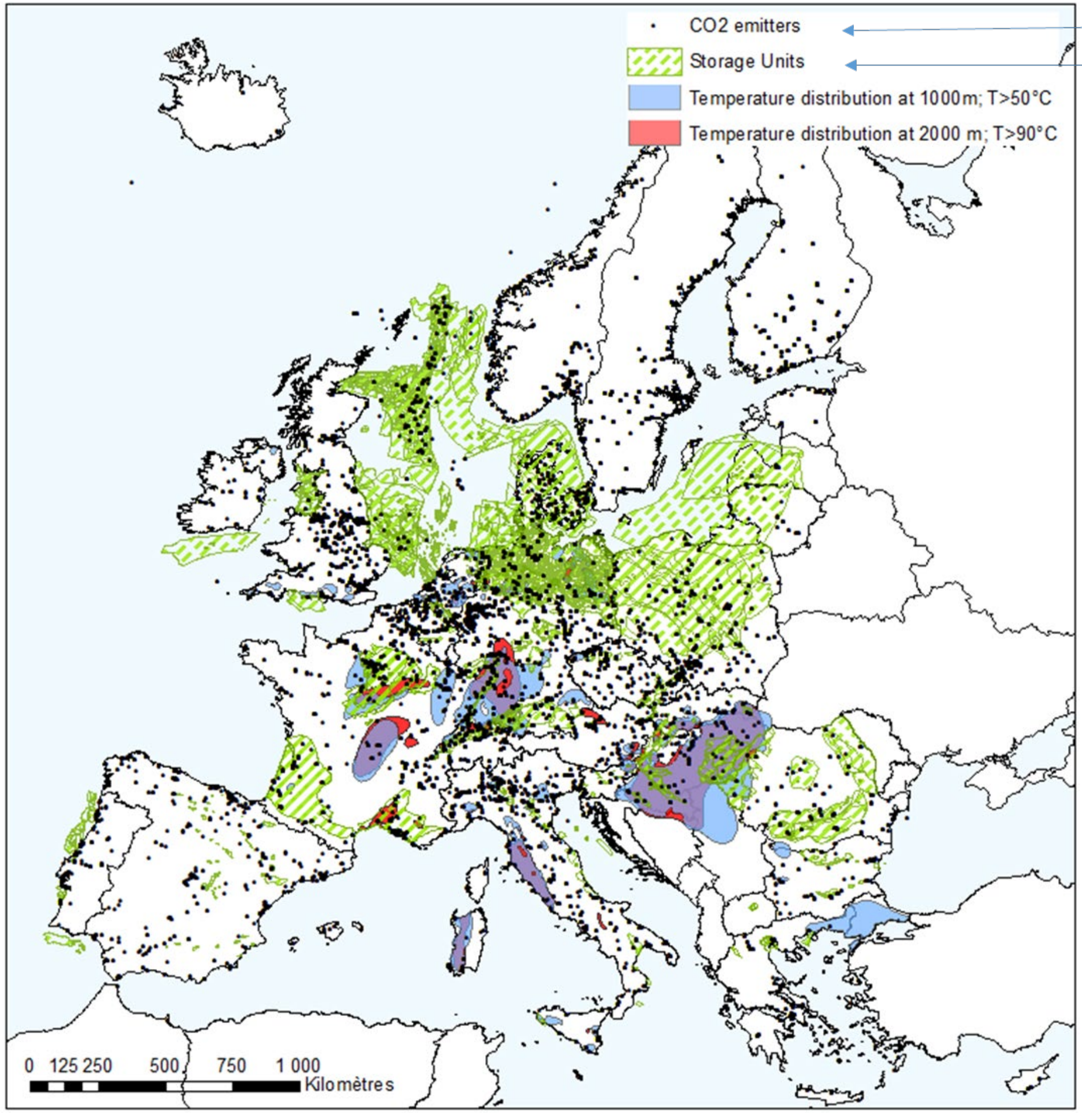
Georisques database

AtlasGTH projet

CO2STOP project improved for Hystories project



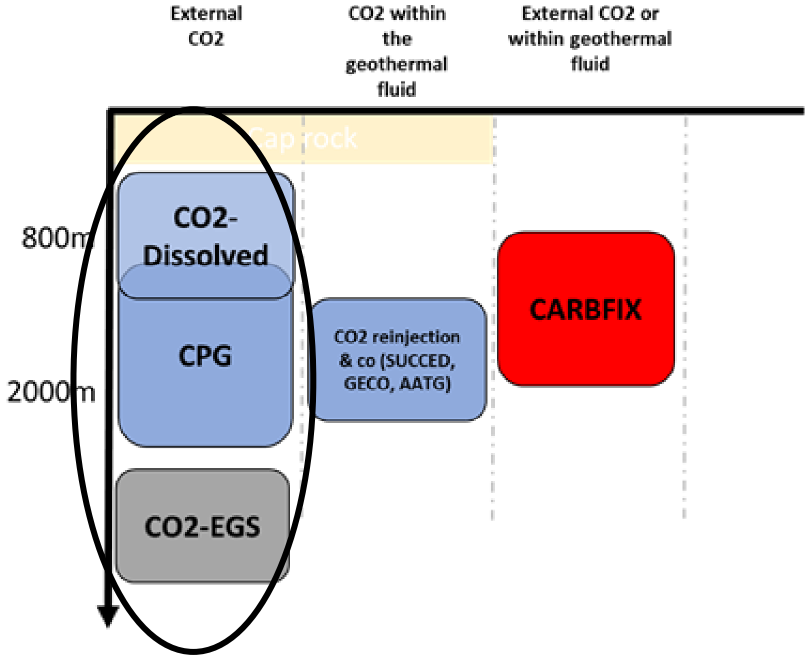
Combining data to assess favourable areas for combined geothermal energy production and CCS



EEA database > 100,000 T/year

CO2STOP project

GeoDH project



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CONCLUSION & RECOMMENDATIONS

CONCLUSION

1) What type of hybrid CCS/geothermal systems are operational and/or described in the literature?

- 150+ papers, 15 concepts (as of end 2022), falling into 3 main categories:
  - ✓ Use of supercritical CO_2 as a heat vector for geothermal energy production
  - ✓ Water-driven geothermal concepts with CO_2 (re)injection either from the geothermal fluid itself or from an external source
  - ✓ Other synergetic uses with lighter hybridization local social and political acceptance for the project
- The development level, from concept paper to demonstrator is highly heterogeneous
- A set of infographics was developed to provide the big picture of each concept and facilitate comparison
- Hybrid use of the underground, in particular with CCS and geothermal energy exploitation, clearly makes sense as part of the actions to be undertaken to mitigate climate change

CONCLUSION

2) What main criteria should be considered to compare these systems?

- Complex task due to large heterogeneity between the levels of description, knowledge, feedback, and overall maturity.

- We have proposed 17 KPIs grouped into 7 categories:
  - ✓ Ambition & Replicability
  - ✓ Integration, Modularity & Scalability
  - ✓ Stakeholder Perception
  - ✓ Readiness
  - ✓ Environmental Risks & Impacts
  - ✓ Technical Complexity & Scientific Challenges
  - ✓ Credible Path to Commercialization

- To provide an overview of all the concepts in terms of ‘performance’, we have produced a series of infographics

- To enable a more quantitative comparison, we have gathered key features in an Excel spreadsheet including a score (1..5) for each of the KPIs… The reader will have the possibility to add his/her own score and calculate a sound weighted average according to personal criteria

CONCLUSION

2) What main criteria should be considered to compare these systems?

- The most ambitious concepts in terms of claimed high energy delivery and high CO_2 storage potential (CO_2-EGS, CPG-ES, Earth Battery, Hybrid Energy Systems):
  - ✓ rely on relatively high technological complexity that still needs to be proven to confirm feasibility;
  - ✓ require that large amounts of CO_2 can be made available at the selected site.
- Lower capacity systems, such as most of the water-driven geothermal concepts with CO_2 (re)injection:
  - ✓ have the advantage of using simpler and more mature technologies, making technical feasibility more likely to be achievable or already proven by existing demonstrators (CarbFix, CLEAG, CO2 re-injection);
  - ✓ need a high level of replicability and deployment to have measurable environmental impact

RECOMMENDATIONS

- Public bodies adapt the conditions and rules of their future calls for proposals on this topic, adding replicability potential and LCA performance conditions as key criteria for the evaluation of early stage proposals;
- Regulators and policy makers adapt regulations to facilitate the deployment of innovative hybrid projects using the subsurface, at least for the pilot phase;
- New subsurface data acquisition campaigns can benefit from adapted incentivized public co-funding and, in return, the results should be made available to the scientific community so that future projects, possibly dedicated to pure geothermal energy production or pure CCS, or a combination of both, can benefit from them and significantly reduce the initial investment of the pre-feasibility phase;
- Governments adjust their policies to strengthen and broaden carbon pricing mechanisms, possibly by making them more attractive to good performers and more punitive for others;
- The scientific community, industrial companies, and public authorities (city, state/region, country) adapt their narratives to convince the public of the absolute necessity of setting up these types of geothermal and CCS projects. This notably requires close cooperation with sociologists and communication professionals before any definitive decision on setting up a project.

Thank you for your attention!