Overview of technologies combining geothermal energy and CCS: mutual benefits and contributions to Net Zero targets

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San Servolo Island, Venice
23 May 2024

Who are we?

Our internationally recognised name is the IEA Greenhouse Gas R&D Programme (IEAGHG). We are a Technology Collaboration Programme (TCP) and are a part of the International Energy Agency's (IEA's) Energy Technology Network.

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Project Overview

- **Aim**: to provide a dispassionate review of different geothermal energy concepts and CCUS where there might be potential for combining two technologies.
- **Study proposed by**: IEAGHG
- **Contractor:** BRGM
- **Principal researchers**: Christophe Kervevan (PM), Annick Loschetter, Rowena Stead, Chrystel Dezayes, Thomas Le Guénan.
- **Kick-off:** April 2022

Objectives and Scope of Work

- What type of hybrid CCS/geothermal systems are operational and/or described in the literature?
- What main criteria can be considered to compare these systems?
- What regions have the most favourable features for future implementation of these technologies?

WP1 – Literature review

WP2 – Screening methodology

WP3 – Mapping of favourable areas

Outputs and Impact

- **Final Report (130pp), Appendices, Excel Sheet**
  - Reviewed by seven experts in the field
  - >100 requests for report prior to open publication
  - Published August 2023 – available at www.ieaghg.org
- **Webinar**
  - >120 at live event
  - 780 views on YouTube
- **Presentations at conferences**
  - EGW 2023, GET 2023, EGU 2024, GHGT-17 2024
- **Review paper** – in preparation

OVERVIEW OF TECHNOLOGIES COMBINING GEOTHERMAL ENERGY AND CCS: MUTUAL BENEFITS AND CONTRIBUTIONS TO NET ZERO TARGETS

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CO_2GeoNet Open Forum, 21 May 2024

Report IEA/CON/22/283 undertaken for IEAGHG (2022-2023) published 02/2024

INTRODUCTION

Context

Geothermal & Heat storage
Geothermal & Lithium (or other minerals/metals)
Geothermal & Gases? (H2 / He…)

Geothermal & CCS

- Double environmental benefits
- Double source of revenues

… and Content

1. Literature review: >150 publications (+ interviews)
   Identify and categorise hybrid concepts
2. Screening methodology:
   Comparison between the hybrid concepts
3. Methodological proposal for assessing the geographical areas potentially compatible with the hybrid concepts

1 – LITERATURE REVIEW

Identification of hybrid concepts and their classification : 4 categories

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)

1 – LITERATURE REVIEW

Identification of hybrid concepts and their classification: 15 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)

«Competitive» concepts that require similar geological features

- CPG
  CO_2 Plume Geothermal
  - CO_2-Bulk Energy Storage
    Earth Battery
  - CPG-ES (Energy Storage)
    CPG-F (Flexible)

CPG and variants

Depth >800m to reach supercritical CO_2

Initialization with CO_2 to form a CO_2 plume
Then exploitation of supercritical CO_2 to produce heat and/or electricity

Possible variations to add energy storage services

- CO_2-DISSOLVED
- Geothermal BECCS
  (Bio Energy with CCS)
- Geothermal for CCS
  (dissolved)

Heat mining with injection of CO_2 in dissolved form for CO_2 storage

No initialization
Heat mining with brine, different possible outlets for heat: pre-heating in a biomass plant (geothermal BECCS), capture process, other (such as District Heating Network)
CO_2 from an « external source » is co-injected with geothermal brine in dissolved form

- Geothermal for capture

geothermal heat can be used for capture

- Hybrid energy system
- Synergy through
  Pressure management
- Coexistence in the same
  reservoir

Coexistence and synergy of heat mining and CO_2 storage in the same formation

Different possible layouts to mutualize prospection, exploration, data, infrastructure and benefit from pressure management

Concepts intrinsically linked to specific geological features

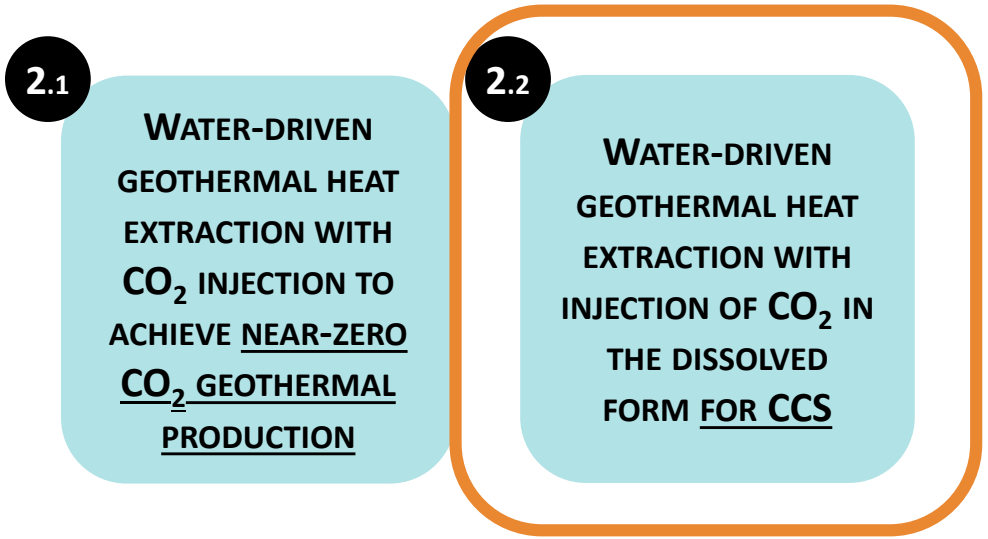
Benefiting from opportunities

Dealing with constraints

- Carbfix – hybrid geothermal
  Takes benefit of the highly reactive nature of rocks in some geological contexts to target rapid mineralization
- CLEAG-AATG
  (CloZEd Loop Energy-AG)
  Addresses geological contexts where fluid contains methane. It optimizes fluid valorization and stores emissions
- SC-CO_2 in EOR/EGR
  (Heat Mining)
  Progress conventional EOR/EGR to co-produce geothermal energy Heat mining
- CO_2-EGS (Enhanced
  /Engineered Geothermal)
  Extension of heat mining to fractured systems, with more complex surface and subsurface engineering
- Reinjection
  A solution to deploy near-zero geoth. exploitation in contexts where the geothermal fluid contains CO_2

1 – LITERATURE REVIEW

Example of concepts (1)



CO_2-DISSOLVED-LIKE CONCEPT

1.7 km

60 to 80°C

External CO_2 input ~1.5 kg/s

Geothermal fluid ~100 kg/s

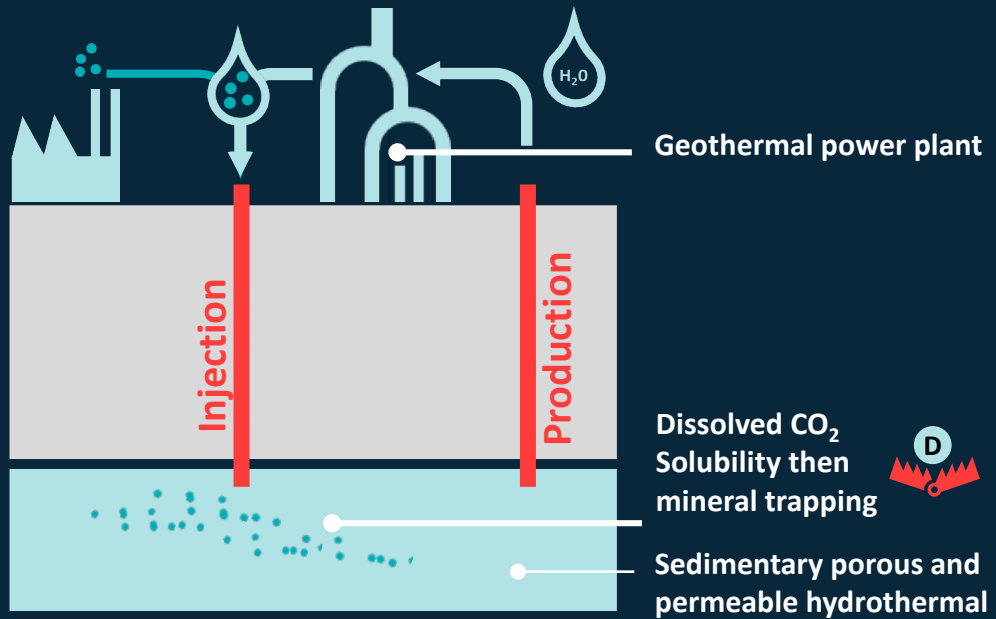
Breakthrough of dissolved CO_2 in the production well after some years

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

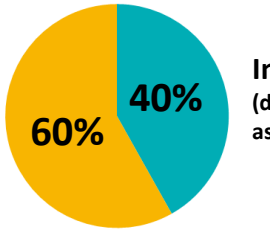
First published in 2014
Several scientific articles
Pilot in planning in France
Cradle: France



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. 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

1 – LITERATURE REVIEW

Example of concepts (2)

1

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

CO_2-EGS – Enhanced Geothermal System

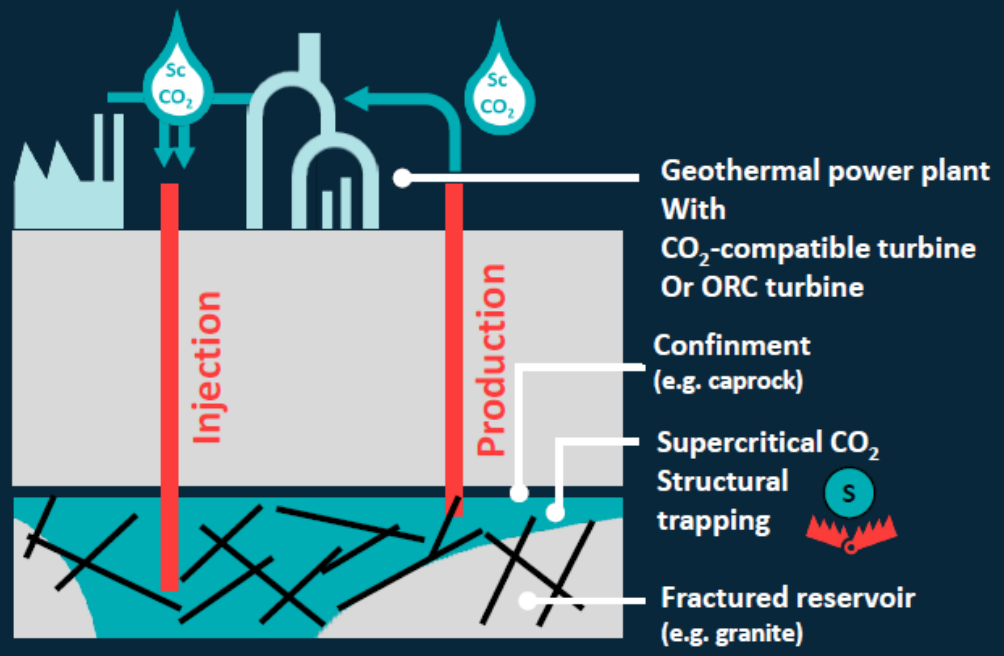
3 - 6 km

160 to 300°C

External input 5-15 kg/s

Supercritical CO2 100-300 kg/s

5% loss



+ Outstanding performances by combining non-intermittent renewable energy production and CO2 storage from external emitter
Efficiency higher with Sc-CO2 than with water

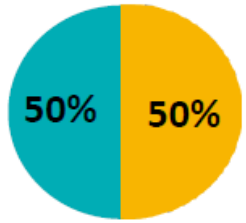
– High investment cost
High development risks
Tricky design for long-term exploitation
CO_2 confinement and risks/impacts issues

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

CO2-EGS consists of using supercritical CO_2 (ScCO2) instead of brine as 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, the energy efficiency is higher with CO_2 than with water/brine due to higher mobility and thermosiphon effect. Efficiency improvement around +50% 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 CO2 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 significant amount of CO_2 storage after 30 years of operation.

SERVICES PROVIDED

- Energy production: 5 – 15 MWe
- CO2 storage: 2 – 15 Mt CO_2 over 30 years
- Energy Storage Service



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

IMPLEMENTATION COMPLEXITY

2-5 deep wells

Stim.

Initialization (months)

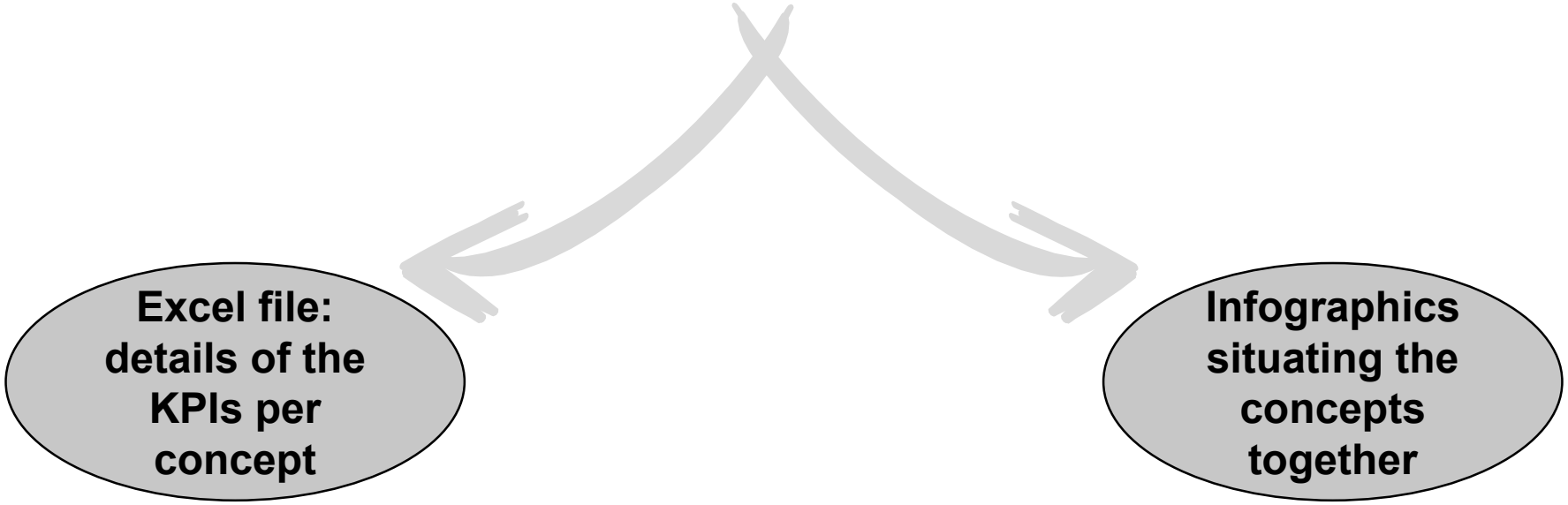
Seismicity issue

Confinment Sc CO_2

2 - WHAT MAIN CRITERIA CAN BE CONSIDERED TO COMPARE THESE SYSTEMS?

Screening methodology: Enabling comparison between concepts

- Created a set of key performance indicators (KPI) to apply to each concept.
- Established an analysis grid for comparing these concepts and their actual or expected performance.
- Adopted a qualitative or semi-quantitative scoring of the KPIs.



2 - SCREENING METHODOLOGY: ENABLING COMPARISON BETWEEN CONCEPTS

AMBITIONS & REPLICABILITY
- ▶ Contribution to energetic and environmental challenges raised by climate change, i.e. decarbonation through:
  - renewable energy production
  - CO2 storage
  - energy storage
- ▶ Replicability (considering the underground conditions)
- ▶ Worldwide potential for energy production (individual potential x replicability potential)
- ▶ Worldwide potential for CO2 storage (individual potential x replicability potential)

INTEGRATION, MODULARITY & SCALABILITY
- ▶ **Upstream requirements:** does the concept require an external supply (e.g. CO2)?; are the quantitative and qualitative requirements realistic and are they compatible with the overall system?
- ▶ **Downstream requirements:** are the quantitative and qualitative characteristics of energy production/storage compatible with the energy system?; is the handling of other outputs (if any) feasible?
- ▶ Scalability and adaptability
- ▶ Modularity and "Plug&play declination"

PERCEPTION BY STAKEHOLDERS
- ▶ Legitimacy of the concept

READINESS
- ▶ Proof of performance and of safety

ENVIRONMENTAL RISKS & IMPACTS
- ▶ Surface footprint
- ▶ Water consumption
- ▶ Guarantee of CO2 containment and safety issues
- ▶ Seismic risk (whether natural or controlled)

TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES
- ▶ Engineered technical complexity
- ▶ Degree of i) understanding of thermo-hydro-mechanical and microbio-geochemical phenomena and ii) management of the underground technical design

DERISKED BUSINESS MODEL
- ▶ Development risks
- ▶ Investment cost
- ▶ Economic performance

19 KPI criteria under 7 themes

15 Concepts

	CO_2-EGS		CPG			
AMBITIONS & REPLICABILITY	**3.3**		**4.3**		**2.5**	
▶ The overall objective of the concept should as much as possible contribute to energetic and environmental challenges raised by climate change: - produce renewable energy - store CO2 and contribute to climate change mitigation - offer energy storage service that contribute to system decarbonation	4	▶ The environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO2 from external emitter.	4	▶ The environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO2 from external emitter.	4	▶ The environmenta are very high by con renewable energy pr significant amounts
▶ The concept should be easily replicable considering underground conditions required.	3	▶ The targeted geology is little demanding and the concept could be easily replicated. No water ressource is required. The mobility of CO2 makes it possible to extend the potential of water-driven EGS systems, targeting lower permeability reservoirs or requiring less stimulation. ▶ The proof of concept for water-driven EGS remains limited, so the large theoretical potential should be considered as an upper limit until evidence of technical feasibility. ▶ The becoming of CO2 and guaranteeing the confinement should be considered cautiously and might limit the replicability.	4	▶ The targeted geology requires a porous and permeable aquifer. These geological features are relatively widespread, but coveted for other uses too. ▶ The mobility of CO2 makes it possible to extend the potential of water-driven geothermal systems, targeting lower permeability reservoirs. ▶ The becoming of CO2 and guaranteeing the confinement should be considered cautiously and might limit the replicability.	2	▶ The concept targe especially those exp EGR. The replicabilit reservoirs with suita
▶ The concept should present a worldwide potential as high as possible for energy production (individual potential x replicability potential) to significantly contribute to global energetic and environmental challenges.	3	▶ A single plant produces several (5-15) MWe with a doublet	4	▶ A single plant produces several Mwe (1-6) with a doublet.	1	▶ A single plant pro doublet during a lim

Legend: ▶ Advantage, ▶ Minor drawback or moderate challenge, ▶ Significant drawback or challenge

2 - SCREENING METHODOLOGY: ENABLING COMPARISON BETWEEN CONCEPTS

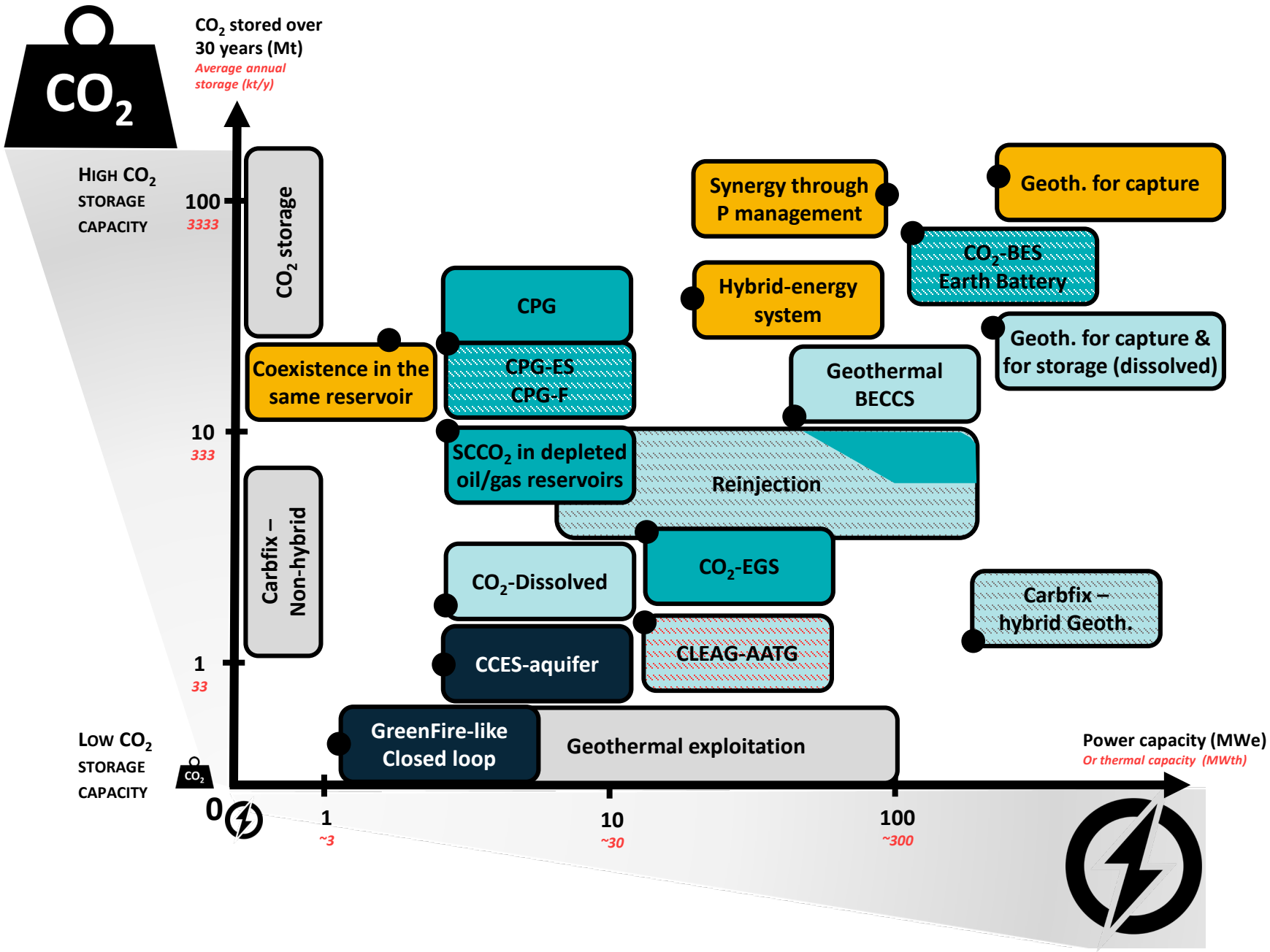
Results at a glance

	CO2-EGS	CPG	SC-CO2 in gas/oil reservoir	CPG-ES	Earth Battery - CO2-BES/TES	Carbfix*-like concept	CO2-reinjection concept	CLEAG-like concept	CO2-Dissolved-like concept	Geothermal BECCS	A reinjection-CCS driven concept	CCS with geothermal energy for capture process	Synergetic use through dual uses in the same reservoir	Synergy through pressure management
AMBITIONS & REPLICABILITY	**3,3**	**4,3**	**2,5**	**3,8**	**4,5**	**2,5**	**3,5**	**3**	**4**	**4,8**	**2,8**	**3,3**	**4**	**4,3**
▶The overall objective of the concept should as much as possible contribute to energetic and environmental challenges raised by climate changes: - produce renewable energy - store CO2 and contribute to climate change mitigation - offer energy storage service that contribute to system decarbonation	4	4	4	5	5	2	2	3	3	4	2	2	4	4
▶The concept should be easily replicable considering underground conditions required.	3	4	2	3	3	2	4	3	5	5	2	3	4	3
▶The concept should present a worldwide potential as high as possible for energy production (individual potential x replicability potential) to significantly contribute to global energetic and environmental challenges.	3	4	1	3	5	4	5	4	4	5	3	3	3	5
▶The concept should present a worldwide potential as high as possible for CO2 storage (individual potential x replicability potential) to significantly contribute to global energetic and environmental challenges.	3	5	3	4	5	2	3	2	4	5	4	5	5	5
INTEGRATION, MODULARITY & SCALABILITY	**3,3**	**3**	**4**	**2,7**	**3**	**4,3**	**3,7**	**4**	**4**	**4,3**	**3,7**	**3,7**	**3,3**	**3**
▶Upstream requirements: If the concept requires external supply (e.g. CO2 from external emitter), the quantitative and qualitative requirements should be in accordance with possible practical supply in order to be embeddable with the overall system.	3	2	4	2	4	4	3	3	5	4	4	4	4	4
▶Downstream requirements: i. the quantitative and qualitative characteristics of energy production/storage should be embeddable with the energy system; ii. handling of other outputs (if any) should be practically feasible.	5	5	5	4	4	5	5	4	3	5	4	4	3	2
▶The concept should be as scalable and adaptable as possible.	2	2	3	2	1	4	3	5	4	4	3	3	3	3
▶Modularity and "Plug&play declination" would facilitate the integration.														
PERCEPTION BY STAKEHOLDERS	**2**	**3**	**4**	**3**	**3**	**5**	**4**	**5**	**3**	**3**	**3**	**3**	**3**	**3**
▶The legitimacy of the concept should be as high as possible for the different stakholders.	2	3	4	3	3	5	4	5	3	3	3	3	3	3
READINESS	**2**	**3**	**4**	**2**	**2**	**5**	**3**	**5**	**4**	**3**	**2**	**3**	**3**	**4**
▶Proofs of performance and of safety should be as high as possible	2	3	4	2	2	5	3	5	4	3	2	3	3	4
ENVIRONMENTAL RISKS & IMPACTS	**3**	**3,8**	**4,3**	**3,5**	**3,5**	**4,3**	**4,3**	**4,3**	**4,3**	**4**	**4**	**3,8**	**3,8**	**4**
▶The surface footprint should be limited	5	5	5	5	4	5	5	5	5	4	5	5	5	5
▶The water consumption should be limited	4	4	4	4	4	4	4	4	4	4	4	4	4	4
▶The confinment of CO2 should be guaranteed for CCS objective and safety issues (leakage)	1	3	5	2	3	5	4	4	4	4	4	3	3	3
▶The seismic risk should be low (either naturally-low or well-managed).	2	3	3	3	3	3	4	4	4	4	3	3	3	4
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	**1**	**3**	**3**	**2**	**2**	**4**	**3,5**	**4,5**	**4,5**	**3,5**	**3**	**3,5**	**3**	**3**
▶The engineered technical complexity (deep wells, multi-lateral wells, stimulations, surface installations, etc.) should be as low as possible, and in adequation with the project positive impacts.	1	3	4	1	1	4	4	5	5	4	3	4	3	3
▶The thermo-hydro-mechanical phenomena, as well as the microbio-geochemical phenomena, should be well understood and the underground technical design should be well-managed in order to avoid detrimental dysfunctions (thermal breakthrough, non-constant heat recovery, consequences of impurities, seismicity, precipitation and clogging in the near-wells and scaling in wells, corrosion in wells and surface installations, perturbation in the reservoir).	1	3	2	3	3	4	3	4	4	3	3	3	3	3
DERISKED BUSINESS MODEL	**1,5**	**3**	**4,5**	**2**	**2,5**	**4**	**3**	**4**	**4**	**4**	**2,5**	**3,5**	**4**	**4**
▶The development risks, which take into account the technical complexity, the level of uncertainties and external factors, present an entry barrier when developing geothermal projects, and should be as low as possible.	1	3	4	2	2	4	3	4	4	4	3	4	4	4
▶The investment cost should be reasonable (high investment cost and initialization duration are hurdles).														
▶The economic performance should be as robust as possible during the project life span (low operating costs, robust efficiency, solid business plan with economic valorization of energy and storage services).	2	3	5	2	3	4	3	4	4	4	2	3	4	4

	AMBITIONS & REPLICABILITY	INTEGRATION, MODULARITY & SCALABILITY	PERCEPTION BY STAKEHOLDERS	READINESS	ENVIRONMENTAL RISKS & IMPACTS	TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	DERISKED BUSINESS MODEL
Carbfix*-like concept	2,5	4,3	5,0	5,0	4,3	4,0	4,0
CLEAG-like concept	3,0	4,0	5,0	5,0	4,3	4,5	4,0
CO2-reinjection concept	3,5	3,7	4,0	3,0	4,3	3,5	3,0

Examples of infographic overviews situating the 15 concepts

AN OVERVIEW



Non-hybrid exploitation/storage

SUPERCRITICAL CO_2 (used as a heat vector for exploitation and/or Energy storage)

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

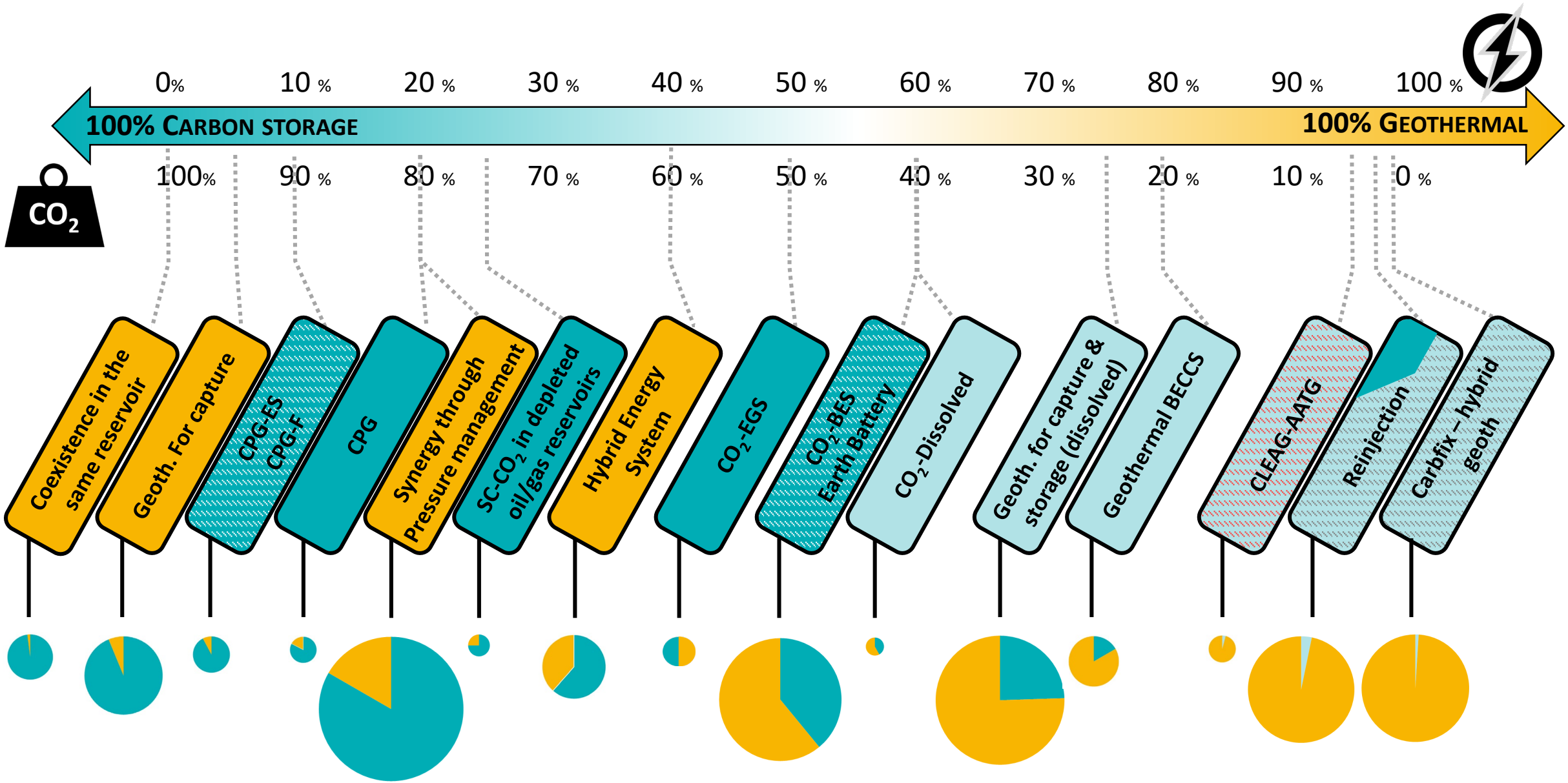
OTHER SYNERGIES

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



Most exhaustive summary of hybrid geothermal-CCS concepts to date:

- Literature review (150+ papers read and analysed): 15 concepts identified and classified according to 4 categories
- Proposed methodology for qualitative and semi-quantitative comparison of concepts
  - ✓ 19 KPIs (classed under 7 themes)
  - ✓ Excel data sheet with screening of the 15 concepts
  - ✓ Standardized infographic visual aids

Enabling:

- Clarification of the landscape of recent or upcoming hybrid concepts combining geothermal and CCS
- Comparison of the concepts (despite heterogeneous data in the literature)
- A framework for your own needs (modification of scores in the XL sheet with your site-specific data)
- Decision making:
  - ✓highlight those concepts with higher potential for deployment and thus prioritize funding
  - ✓first step towards considering these concepts in future decarbonisation plans

Key Messages

- The hybrid use of the subsurface to produce renewable heat/electricity that could largely be decarbonised and/or in conjunction with CCS of an external industrial CO_2 source opens up promising solutions.
- Key criteria are identified and where possible used as comparisons between concepts made, for example total CO_2 stored, energy produced, readiness and subsurface features.
- The most ambitious concepts in terms of high energy delivery and high CO_2 storage potential- (CO_2-EGS, CPG-ES, Earth Battery, Hybrid Energy Systems) rely on high technological complexity that needs to be proven to confirm feasibility.
- Lower capacity systems (e.g. water-driven geothermal concepts with CO_2 reinjection), 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, CO_2 re-injection).
- Future work on the economic evaluation will need to accompany pilot projects to assess the economic feasibility, a feature lacking in many desk based studies to date.
- Engagement across multiple stakeholders are necessary to move concepts to development.

Download the report here

Acknowledgements: we are grateful to IEAGHG for proposing and funding this topic and for interesting scientific discussions and debates as part of this work.

The work has been published in the IEAGHG technical report 2023-02, August 2023
Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS)

IEAGHG upcoming events

7th International Workshop on Offshore Geologic CO2 Storage: September 17-19th Port Arthur, Texas (with GCCC)

International Workshop on Offshore Geologic CO_2 Storage