Technology Collaboration Programme
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Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report
2023-02
August 2023

PROSPECTIVE INTEGRATION OF GEOTHERMAL ENERGY WITH CARBON CAPTURE AND STORAGE

IEA GREENHOUSE GAS R&D PROGRAMME

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ACKNOWLEDGEMENTS AND CITATIONS

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The report should be cited in literature as follows: 'IEAGHG, "Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS)", 2023-02, August 2023'

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PROSPECTIVE INTEGRATION OF GEOTHERMAL ENERGY WITH CARBON CAPTURE AND STORAGE (CCS)

(IEA/CON/22/283)

The aim of the study is to provide a dispassionate review and overview of scenarios where geothermal energy and CO_2 utilisation and storage technologies can be combined for mutual benefit and contribute to Net Zero targets. Sourced from a rich body of literature from global research institutes and some demonstration projects many of the concepts identified have been conceptualised over the past 20 years and are still in the early concept stage. These concepts have been categorised, described and evaluated using qualitative and quantitative methods. And a map based screening exercise useful for initial evaluation of areas suitable for combined synergies has been undertaken.

Key Messages

- The use of subsurface resources will play a central role among the many solutions necessary for climate-change mitigation and to keep the Paris Agreements on track. These can comprise both shallow (near surface) and deep geological (>0.8km) resources.
- The hybrid use of the subsurface to produce renewable heat or electricity that could largely be decarbonised and /or in conjunction with Carbon Capture and Storage (CCS) of an external industrial CO_2 source opens up promising solutions.
- Most of the concepts described in this work developed over the past 20 years are at conceptual stages and sourced from a rich body of literature (over 150 papers) these concepts largely need to be tested before demonstrating their potential for deployment.
- Concepts are grouped into main themes:
  - Use of supercritical CO_2 as a heat vector for geothermal energy production – this includes CPG (CO_2 Plume Geothermal), CO_2-EGS (Enhanced Geothermal Systems), Heat production from former oil and gas reservoirs, CPG-ES (Energy Storage), and Earth Battery.
  - Water-driven geothermal concepts with CO_2 injection or re-injection generally dissolved in the geothermal brine. The source of the CO_2 is either from an external source, e.g. CO_2-Dissolved and Geothermal BECCS, or from the geothermal fluid e.g. CarbFix, CLEAG-AATG and CO_2-reinjection concepts. Of these, pilots are in preparation in France, operational in Iceland or about to start in Croatia, Italy, New Zealand and Turkey.
  - Other synergetic uses - CCS with improved efficiency in the capture process by using geothermal energy, synergy through dual non-competitive use in the same reservoir, and synergetic use through pressure management.
  - Borderline concepts were also discussed in brief, but otherwise deemed out of scope for the study.
- Key criteria are identified and where possible used as comparisons between concepts made, for example, total CO_2 stored, energy produced, overview of research and path to commerciality, 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, such as most of the 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). These

concepts require high level of replicability if they are going to have a measurable environmental impact on reducing CO_2 emissions, but are potentially easier to manage permitting and gain social acceptance.

- First level screening is possible with the use of publicly available data to produce maps that co-locate the most favourable areas to combine geothermal power and some form of CCS while being in relative close proximity to an industrial CO2 emission source or within reach of a transportation network. A broad brush approach for France highlights the Paris and Marseilles areas as being most ideal.
- 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.

Background to the Study

The dual challenge of the present energy and climate crisis offer opportunities for new ways of thinking. A resurgence of interest in geothermal energy combined with maturing carbon capture and storage (CCS) technologies offers a compelling argument to integrate where possible. Since IEAGHG conducted a high-level review in 2010[1] there have been a variety of new concepts developed at concept and demonstration stage.

Geothermal facilities for district heating and electricity production have been developed for over a hundred years and CCS is growing momentum, albeit at a slower pace than required to meet global climate goals. In 2020, the total worldwide geothermal power capacity rose to 15.7 GWe (EGEC, 2022) albeit with low global growth rates of 4% per annum over the last 10 years. Nonetheless, a massive gap persists between the current deployment rate and that needed to reduce global anthropogenic emissions to net zero. According to the IEA's Net-Zero 2050 report (IEA, 2021), the geothermal electrical capacity should reach 126 GWe in 2050 and the electrical capacity of fossil fuels with CCUS (Carbon Capture, Utilization and Storage) should reach 394 GWe in 2050 (in comparison to the 1 GWe already installed). So geothermal power will be a niche market activity.

Barriers to deployment include: lack of competitiveness; large initial expenditure; and geological constraints for geothermal projects and CCS. The latter suffers from a lack of economic and commercial incentives, lack of political and public support and environmental concerns to name a few – although the political landscape is shifting and with it fiscal and policy support. There are mutual benefits that could potentially arise in projects that synergise the two systems, these might include cost benefits and additional sources of revenues, even access to financing might be improved with promise of low-emissions. In some cases energy performance of subsurface geothermal could be increased with the use of CO_2 as a heat vector.

Scope of Work

The aim of the study is to provide a dispassionate review and overview of different geothermal energy concepts and CO_2 utilisation and storage technologies, where there may be potential for combining the two for mutual benefit. This contract was awarded to BRGM, France. These concepts are concisely described as the result of a comprehensive literature review and an overview given by way of tables and infographics and their technical merits noted and critical evaluation given. Volumetric use and or storage of CO_2 and heat energy recovery is first order estimated. Pro's and con's for each concept is explored and an indication of where they sit within their stage of research and path to commerciality is given.

The CO_2 storage and geothermal energy concepts that are addressed either:

- share CO_2 as a fluid that circulates through a reservoir and not only extracts heat but is also stored

1. [1] Geothermal energy and Storage. 2010/TR3

-occur in reservoirs where geothermal energy extraction and CO_2 storage interacts indirectly via pressure perturbations,

- utilize shared subsurface installations such as wells,

- or use geothermal energy converted on surface to electricity or heat for meeting energy needs in CO_2-capture facilities.

The concepts are evaluated and compared by means of a set of characteristics and key performance criteria which include surface and sub-surface requirements. The methodology is clearly stated.

Lastly, a first-order screening methodology is applied to evaluate regions that are favourable for hybrid CO_2 capture and storage with geothermal. This includes data that aids considering energy demand (built environment), CO_2 emitters, and geological requirements (e.g. thermal regime, reservoirs, seals etc). These have been applied at a global, continent and country/regional scale and then focussed on Europe with more detail given to France.

Approach. The study sought to provide a comprehensive and dispassionate review of all combined use of geothermal and CCS at conceptual or pilot/demonstration stage.

This was largely achieved by a substantial literature review, summarising of information and then creation of tables and infographics containing key information for each of the 15 identified concepts.

Once all the data gathering stage was complete BRGM then conducted a series of brain storming sessions to define a set of 17 key comparative criteria to allow comparison between concepts in the form of a grid. A rating system was developed and clearly described. Key select criteria were also drawn out by way of comparison figures such as CO_2 storage capacity vs power generation capacity and the operating fluid, indexes of services ratio and where the system sits between a continuum of pure CCS and pure geothermal.

Lastly, open access data was gathered from global to regional scale databases across a variety of sources that might aid in identifying regions that would favour a combination of geothermal and CCS. These data include emissions sources, and geological data (sedimentary basins, thermal gradients, reservoirs etc). These were combined for two case studies to demonstrate a high-level screening approach, two maps were produced for for Europe a detailed example for France.

Findings of the Study

Benefits to combining geothermal heat extraction with some form of CO_2 capture and storage are seen as follows:

- Efficiency improvement of heat transfer by using CO_2 as a heat vector
- Economic gains by mutualising and optimising costs e.g. data exploration, infrastructure, operational management.
- There is a degree of overlap in geological features required in terms of high porosity and permeability of a reservoir but these differ in terms of temperature requirements.

There are considerable differences between the behaviour of CO_2 and H_2O (or brine) at temperature and depth (pressure) in terms of phase, density, viscosity, compressibility, and heat transfer which impacts how fluid might circulate in a reservoir and how effective it is for heat transfer e.g. CO_2 is highly compressible with a low viscosity whereas H_2O has a constant density and high specific heat level (Olasolo et al, 2018). Generally, H_2O will act to transfer heat more readily due to its mass heat capacity but CO_2 is more mobile due to a higher viscosity which lends itself to higher extraction rates. Factoring in the variety of configurations of temperature and pressure, CO_2 generally outperforms water as a heat vector by a factor of 1.5 to 3, an exception would be in highly permeable formations where viscosity becomes less relevant and the advantage of using CO_2 less significant. Other factors to consider are the solubility of CO_2 in brine, which is a factor of brine salinity, temperature and pressure.

Concepts and projects that combine geothermal energy use with CCUS

The main concepts explored in the main body of the report are grouped into four categories (figure 1):

- Use of supercritical CO_2 as a heat vector that extract heat from a subsurface reservoir and where CO_2 has been sourced from a capture facility;
- Geothermal energy is produced with water-dominated fluid, and where CO_2 is co-injected with water (generally in the dissolved form);
- More indirect concepts where geothermal energy production and CCS overlap, e.g. shared reservoir and interaction are via pressure perturbations, or using shared subsurface installations or using geothermal energy to meet energy requirements of a CO_2 capture facility;
- Borderline projects, introduced briefly but considered out of the project scope.

These concepts are described as a result of a substantial literature review, the main features are described, tabulated and an infographic prepared with high level (and consistent) information, each concept is also compared against a set of key parameters.

- **Use of supercritical CO_2 as a heat vector for geothermal exploitation and/or energy storage**
  - **CPG** (CO_2 Plume Geothermal) – where CO_2 is used instead of brine as a heat vector in conventional hydrothermal reservoirs with simultaneous CO_2 storage. CPG can provide heat extraction rates of up to three times greater than those of traditional water-based systems. CO_2 storage is not the primary objective – however several tens of Mt CO_2 can be stored over its life cycle. Projects will need to satisfy the same conformance and monitoring as a standard CCS project. Investments costs are high. Feasibility pilots have been assessed at the CO_2 storage sites Aquistore, Canada and SECARB, Cranfield Mississippi.
  - **CO_2 EGS** (Enhanced Geothermal Systems) – uses supercritical CO_2 instead of brine as a heat vector in fractured dry or water saturated rock (e.g. crystalline). Drilled to 3-6 km depth the reservoir requires stimulation to increase permeability through fractures. Water driven EGS is at pilot/demonstration stage whereas CO_2 EGS is still conceptual, and owing to lower porosity reservoirs CO_2 storage potential is much lower than CPG. The reservoirs are also potentially open systems making storage security a further issue, fluid-rock interactions may also pose reservoir management issues. Investment costs are high and there are no feasibility, pilot study or patent registered against this technology at this time. Induced seismicity may also pose problems and appropriate monitoring, measurement and verification would need to be established.
  - **CO_2-EOR/EGR** (Enhanced Oil Recovery or Gas Recovery) – novel technologies have been proposed to progress conventional EOR/EGR to co-produce geothermal energy with supercritical CO_2 as a heat vector. Technical challenges may include residual methane and H_2S causing corrosion of surface equipment and the integrity of legacy wells. Tested at SECARB, Cranfield at a depth of 3.2km but the thermosiphon was not sustainable contrary to model predictions.
  - **Underground Thermal Energy Storage (UTES),** whereby excess energy from for example renewable energy sources or excess heat from a waste-to-energy plant is used to heat or compress a working fluid which is stored underground and energy retrieved when required by the grid to balance supply and demand. CO_2 may potentially act as the working fluid for these technologies e.g. **CPG-Energy Storage** – a modification to the CPG method, requiring two aquifers, a conceptual design proposed in 2016 with no case studies. **Earth Battery** (CO_2 Bulk Energy Storage (BES)). BES refers to energy storage that has large energy capacity and changes to discharge over a period of a few hours. Buscheck et al (2016, 2014) and Ogland-Hand et al (2021, 2019) proposed a concept in a permeable reservoir (3-5 km deep) that combines

geothermal energy (brine and CO_2 as fluid vectors), CO_2 storage, and bulk energy storage with a CO_2-pressurised cushion gas. With four concentric rings of wells (~42-75 wells) CO_2 is injected into ring 2 and the pressure managed by an outer third ring of brine injection wells causing a pressure barrier and outer ring of brine production wells and inner ring of brine/CO_2 production wells. An internal cushion of CO_2 is created or hydraulic mound and injected cold brine warms up as it migrates to the outside of the system. A case study is proposed in Wyoming.

- **Water driven geothermal heat extraction with CO_2 reinjection.** There are a variety of closely related and physically co-located projects, pilots and demonstration projects that fall under this category. These are presented and then categorised, and include Carbfix, GECO, SUCCEED; New Zealand initiative; CO_2-Dissolved; and AAT-G/CLEAG (table 1). These have then been categorised into concepts: Carbfix-like; CO_2-reinjection; CO_2-Dissolved; CLEAG-like; CCS driven concept to compensate energetic requirements and Geothermal BECCS concept.
    - **Carbfix-like:** whereby CO_2 is injected (dissolved in water) into mafic and ultra-mafic rocks where it mineralises and is stored, as demonstrated in Iceland since 2011. The provenance of the CO_2 may be sourced from geothermal steam for power generation, thereby improving the environmental performance of geothermal power or by other sources such as direct air capture (DAC). A similar concept, albeit with differing geochemical reactions has been recently announced in New-Zealand[2]
    - **CO_2-reinjection:** in some contexts (e.g. Turkey, Iceland, Italy and New Zealand) the geothermal fluid has a significant CO_2 content (can be over 25% by weight pushing the greenhouse gas emission of a power plant beyond that of a coal fired plant) and the life cycle assessment (LCA) performance of the plant is significantly penalised. This concept captures the CO_2 (and other naturally occurring gasses such as NH_3, N_2, CH_4, H_2S, and H_2) and reinject them entirely dissolved in the geothermal fluid thereby producing geothermal energy with near net-zero emissions. Solubility can be a factor for achieving total dissolution. Reinjection has been tested in Hijiori, Ogachi (Japan), Coso (USA), and Puna (Hawaii), modelling studies performed and projects in development are in Kızıldere, Turkey and Castelnuovo, Italy (Table 1).
    - **CLEAG (CloZEd Loop Energy-AG)-like:** named after the company that developed the first power plant in Draškovec, Croatia in 2013. This is effectively a closed-loop hydrothermal geothermal power plant combined with near-zero emission natural-gas-fuelled thermal power plant. Energy is produced by hot geothermal fluids and by methane separated from the geothermal fluids and burned in a gas engine generating both electricity and heat for local consumption. CO_2 is captured from the geothermal fluid and from the gas engine and then co-injected with cooled brine into the geothermal reservoir to be stored. Replicability may be hampered by the high CH_4 content of the brine, however emissions avoided are very positive.
    - **CO_2-DISSOLVED:** whereby a conventional geothermal doublet in a hydrothermal aquifer with brine as a fluid vector is utilised and has simultaneous CO_2 storage in the form of CO_2 dissolved in the reinjected brine. Due to the solubility limit of CO_2 in brine, it is adapted to small CO_2 industrial emitters (ca. <150,000 t/year). And unlike CPG, CO_2 is injected and stored in entirely dissolved form in the saline aquifer. Any CO_2 capture technology is compatible with CO_2-DISSOLVED but most of the published studies rely on the aqueous-based Pi-CO_2 capture technology, which is particularly well adapted to CO_2-DISSOLVED as it can directly provide carbonated water (that can be reinjected in the reservoir) rather than a CO_2 gas phase (that has to be dissolved in the injection well). The temperature target of the geothermal resource, in the range of 60-80°C, aims at producing heat and not electricity, assuming that the recovered energy can be exploited locally in industrial processing, district heating, etc. Initially proposed by BRGM (in 2014) who coordinates the technology development in collaboration with several

[2] https://www.thinkgeoenergy.com/nz-geothermal-institute-receives-funding-for-greenhouse-gas-capture-project/

academic and industrial partners. Ongoing work is aimed at preparing the first CO_2 injection tests in an existing geothermal doublet, as a preliminary phase before proceeding with the first demonstrator of the full chain (capture, injection, storage, geothermal heat production) at an industrial site. Despite the relatively small quantity of CO_2 sequestered per well the concept has high replicability and may provide solutions to decarbonize areas with geothermal potential.

  - **Geothermal- BECCS (Bio Energy with Carbon Capture and Storage):** Titus et al (2022) introduced a potential modification to classic BECCS with a geothermal component in order to improve the environmental and energy performance of the system. Similar to CO_2-DISSOLVED it differs in a few ways: the source of the CO_2 is from biomass; the geothermal heat is used in combination with the biomass energy to boost power production; and it targets larger power plants (around 100 MWe) and higher CO_2 storage (0.25-0.63 Mt/year). The negative emissions intensity of the whole system is between -200 and -700 g CO_2/kWh.
  - **CCS-driven concepts:** consists of injecting CO_2 from an external emitter and in dissolved form using the reinjection well of a geothermal doublet, and using the brine for energy production, it differs from CO2-Dissolved in that the philosophy originates from CCS and therefore the scale of the concept is designed to fulfil CCS facility requirements (e.g. 116 kg/s CO2 captured flux and ~2200kg/s geothermal fluid flow, with 15 injection wells and 15 production wells). Note this is based on one scientific article.
- **Other synergetic uses**
  - **Pressure management:** whereby the production of brine to relieve pressure in a CO_2 storage development may also be used for geothermal heat/electricity production, this could potentially improve the performance of both CCS and geothermal energy exploitation, although water management could provide extra challenges.
  - **Dual non-competitive use in the same reservoir:** proposed by Tillner et al (2013) with a case study in Germany, geothermal heat extraction and CO_2 storage are located 7 km apart, but in all other cases are independent of each other.
  - **Hybrid energy systems using both technologies:** Buscheck and Upadhye (2021) propose a hybrid approach to produce energy with near-zero carbon emissions (or negative emissions if biomass is used). Geothermal energy is used to pre-heat the fluid before combustion, heat storage and oxy-combustion are combined to generate electricity. CO_2 storage of supercritical CO_2 is envisaged in a reservoir with brine extraction for geothermal heat, and a secondary shallower reservoir used for reinjection of brine and thermal heat storage.
  - **Carbon capture process improved by using geothermal energy:** Davidson et al (2017) investigated the potential to use geothermal energy to provide boiler feedwater pre-heating – theoretical results indicate a promising performance of using geothermal energy (at 150°C) to increase the benefits of CCS with power load associated with a MEA (MonoEthanolAmine)-based capture technology that could be offset by roughly 7%.The CO_2 storage reservoir is wholly separate from the geothermal aquifer in this scenario.
- **Borderline concepts**
  - **Compressed CO_2 Energy Storage (CCES)**
  - **Closed-loop geothermal exploitation with supercritical CO2 as a working fluid**

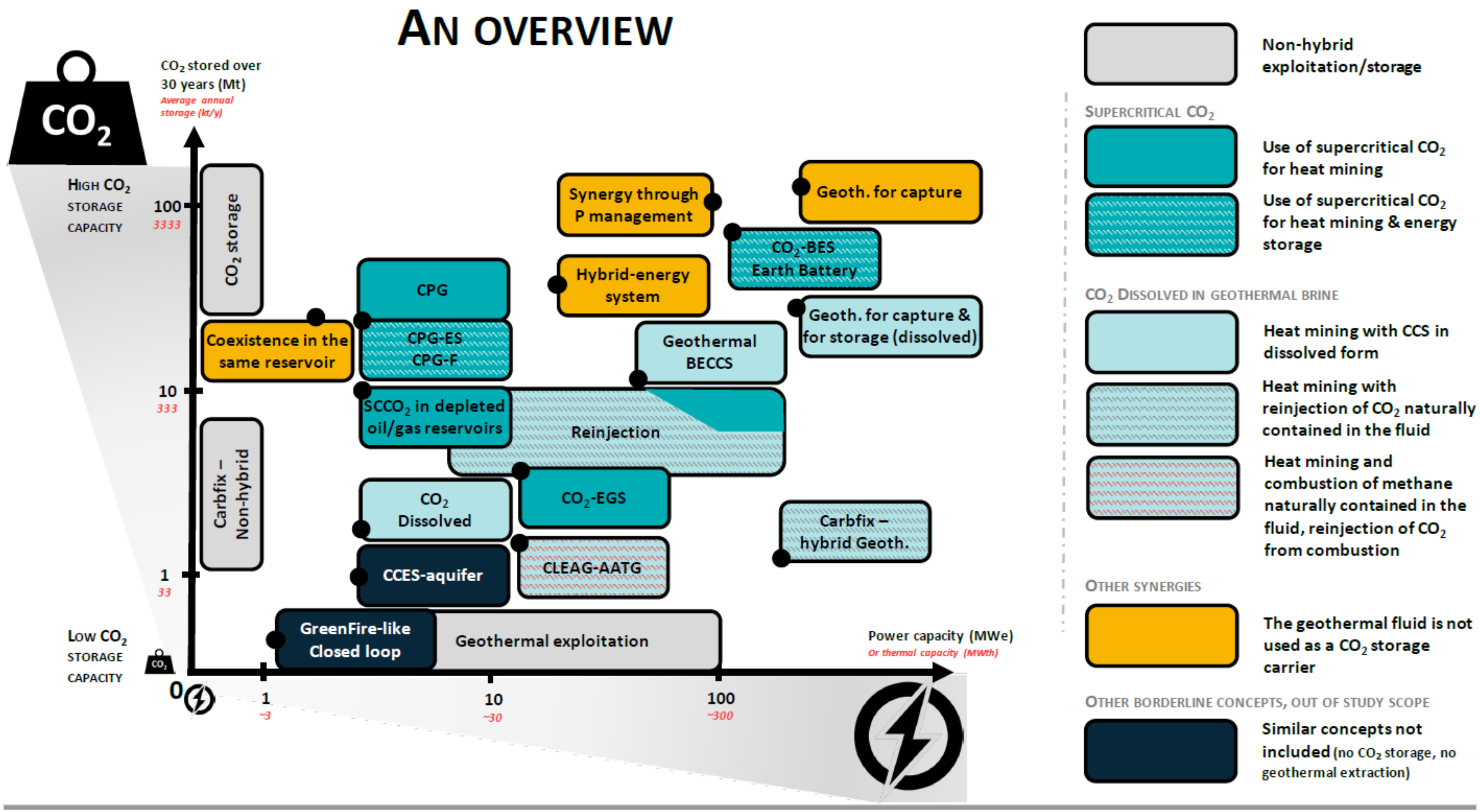

Figure 1: Comparison of CO_2 storage capacity vs power generation capacity for the hybrid concepts identified in this study and end-members.

	Projects [Industrial]	Depth (m)	T° (°C)	Injection (kt/year)	Main trapping mechanism	Description	Progress	Reference
Hellisheidi (shallow reservoir) [Iceland]	Carbfix GECO SUCCEED	500	20-50	**0.23 (obj: 2.2)** Dissolved	Mineral	The project demonstrated that 95% of the CO_2 can be mineralized as calcite in a shallow basaltic reservoir (20-50°C).	2012-2016	Matter et al., 2011, 2016; Snæbjörnsdóttir et al., 2020, etc.
Hellisheidi (deep reservoir) [Iceland]	Carbfix GECO SUCCEED [OR]	750	260	**12 (obj: 33)** Dissolved	Mineral	Flash-unit power plant. 303 MWe. Basaltic formations CO_2 content in the geothermal fluid: around **0.1%** The project demonstrated that 60% of the CO_2 can be mineralized in basaltic geothermal reservoir	Started in 2014	Gunnarsson et al., 2018; Sigfússon et al., 2018
Nesjavellir [Iceland]	GECO [OR]	1000-1700	200-300	**1** (test phase)	Mineral	Flash-unit power plant. Capacity of 120 MWe and 300 MWth. Basaltic formations. CO_2 content in the geothermal fluid: around **0.1%**	To begin in 2022	Galeczka et al., 2022
Ngatamariki and Te Huka [New Zealand]	[Mercury NZ]	Around 2500m	260-280°C	?	?	Reinjection of NCG	In development in 2022.	ThinkGeoenergy[3] BusinessDesk[4] Stuff[5]
Bochum Mule [Germany]	GECO	525 m	25		Solubility and mineral	The German demo site in Bochum is a test site in a sedimentary environment, not linked with a geothermal plant. It consists of a dual flow and injection system. Modelling results showed that carbon dioxide mineralization in the underground of the Bochum GECO site is basically possible (in the form of siderite mineral). These results are pending validation after the demonstration process.	In development in 2022.	
Kızıldere [Turkey]	GECO SUCCEED [Zorlu]	1500	200	**Kızıldere - II: 1** Dissolved **Kızıldere - III: 30** Supercritical	Structural and residual for Kizildere-III	Flash steam turbines. Capacity **Kızıldere** -III 165 MWe Metamorphic formation consisting of marble, quartzite, and schist. Liquid-dominated fluid, 10% steam. CO_2 content: around **1-4%** The injected CO_2 corresponds to a limited part of the CO_2 produced.	In development in 2022.	Durucan et al., 2021; Gunnarsdóttir et al., 2021; Erol et al., 2022
Castelnuovo [Italy]	GECO [Storengy]	3500	280	**30**	Structural and residual	Heat exchanger and ORC turbine Metamorphic steam dominated reservoir	Stand-by.	Gunnarsdóttir et al., 2021; Niknam et al., 2021

[3] https://www.thinkgeoenergy.com/successful-tests-of-capturing-and-reinjecting-geothermal-co2-nz/
[4] https://businessdesk.co.nz/article/energy/mercury-presses-on-with-co2-reinjection
[5] https://www.stuff.co.nz/environment/climate-news/129520035/geothermal-energy-is-already-reliable--soon-it-might-be-carbonneutral-too

				Liquid CO_2-water mixture		CO_2 content: around **8%**. Total NCG reinjection was targeted. Due to permitting issues, is was replaced by the Hveragerði site		
Hveragerði [Iceland]	GECO [OR/ISOR /Storengy]	Storengy (STY) is collaborating with the Iceland GeoSurvey (ISOR) to develop the closed-loop test unit and demonstrate it in a 200°C well in Hveragerði, Iceland. To simulate similar reservoir conditions as in Castelnuovo, the geothermal fluid will be supplied with a CO_2 tank and steam.					In development in 2022.	
Paris basin [France]	CO_2-DISSOLVED	1600-1800	60-80	**Obj:45** Dissolved	Solubility	Heat exchanger for District heating Network Sedimentary basin. CO_2 from external source, injected at **~1.5%**	In preparation	Kervévan et al., 2014, 2017
CLEAG demonstrator [Croatia]	NER 300 [AATG, CLEAG]	1850	110	**60** Dissolved	Solubility	The geothermal fluid contains notably CO_2 and CH4. Methane is used in a gas engine. Heat from geothermal fluid is valorized. Reinjection of CO_2 from the fluid and from the combustion at a rate of **0.6%** by mass (water flow: 320kg/s)	Initial testing in 2014	http://aatg.energy/

Table 1: Pilot and demonstrators for water-driven geothermal heat extraction with CO_2 (re)-injection

Comparison of the main concepts:

For each of the concepts introduced a table has been compiled (table 2) and an infographic created (figure 2) summarising the main characteristics, see below an example for the case of the CO_2 – reinjection concept. Note that conventional TRL levels have not been employed especially as many concepts combine a number of technologies that are inherently at differing maturity levels, instead some scaling factors have been applied such as the year the concept was first described, number of scientific articles and which research groups these originate, existence of a patent and availability of economic information. Characterisation indicators fall into quantitative (e.g. depth) and qualitative or descriptive (e.g. geology).

<table>
<tr><th colspan="3">UNDERGROUND CHARACTERISTICS</th></tr>
<tr><td rowspan="2">Geology and petrophysical properties</td><td colspan="2">The concept targets any geothermal reservoir with high NCG (notably CO_2) content, e.g.:
- metamorphic carbonate in Turkey (marble, quartzite, schist)
- metamorphic micaschist in Italy
The geothermal reservoir consists of permeable matrix and/or permeable fracture/faults.
If injection leads to formation of a supercritical/gas phase, a caprock should guarantee the containment (e.g. clay layer).</td></tr>
<tr><td>Porosity
Permeability</td><td>[3-10] %
[10^{-15}-10^{-14}] m²</td></tr>
<tr><td>Depth</td><td colspan="2">Range [1.5-3.5] km</td></tr>
<tr><td>Dimensions</td><td>Thickness
Extension</td><td>Variable
Kilometre scale - Lateral extension [1-2] km</td></tr>
<tr><td>Temperature</td><td colspan="2">[150-300] °C</td></tr>
<tr><th colspan="3">ENGINEERING</th></tr>
<tr><td>Wells</td><td colspan="2">The number and layout of wells varies, depending on the project size (e.g. tens of wells in Turkey, 3 wells in Italy).
Well design requirements: Generally vertical wells, suitable for high temperature (150-300°C), and CO_2 reinjection.</td></tr>
<tr><td>Surface installations</td><td colspan="2">Steam turbine or heat exchanger and ORC turbine
Fluid pre-processing facilities (separator, scrubber, etc.)
Facilities for injection in dissolved or mixture or supercritical phases, depending on projects characteristics.</td></tr>
<tr><td>Geothermal fluid</td><td colspan="2">Variable flux of geothermal brine: around 1000 kg/s for the Turkish demonstrator, around 12 kg/s for the Italian pilot project.
NCG in the geothermal brine: Several percent (between 1 and 8% by mass for the afore-mentioned demonstrators).
Flux of CO_2 in produced fluid: variable (around 10-30 kg/s for the Turkish demonstrator, around 1 kg/s for the Italian pilot project).
Injection rates for current demonstrators are around 1 kg/s, this corresponds to total reinjection for Italian context and to very partial reinjection for the Turkish concept at the moment.
If the ratio CO_2 flux/brine flux is limited, injection can be done in dissolved form. Otherwise, CO_2 is injected in a brine-liquid mixture or in supercritical form.</td></tr>
<tr><th colspan="3">INTEGRATION</th></tr>
<tr><td>Upstream</td><td colspan="2">No CO_2 requirements from an external source.</td></tr>
<tr><td>Downstream</td><td colspan="2">Requirements:
• Electricity production: connection to suitable voltage grid
• If possible: local valorization of co-produced heat (Combined Heat and Power production to optimize efficiency)</td></tr>
</table>

SERVICES PROVIDED	
Net baseload electricity production	Electricity production: variable (around 200 MWe for Turkish power plant, around 5 MWe for the Italian pilot project)
CO_2 geological storage	The order of magnitude of avoided* CO_2 emissions is 10-600** kt/y, i.e. 0.3-18 Mt over 30 years. * by comparison with a geothermal power plant exploited with current practice, with gases released to the atmosphere. ** 600 kt/y corresponds to a high order of magnitude assuming total reinjection for a power plant such as Kizildere (currently less than 10% of produced CO_2 is reinjected)
FROM CONCEPT TO MARKET	
Readiness	The concept has been discussed for several tens of years. It is currently being thoroughly demonstrated and deployed (demonstrators to be launched in 2022-2023). The number of scientific articles is limited at the moment (10-20).
Proponents	The most active institutes working on this concept are Turkish, Icelandic and Italian, due to the existence of geothermal power plants with high NCG content in these countries.
Availability of economic consideration	Limited information

Table 2: Characteristics of the CO_2-reinjection concept

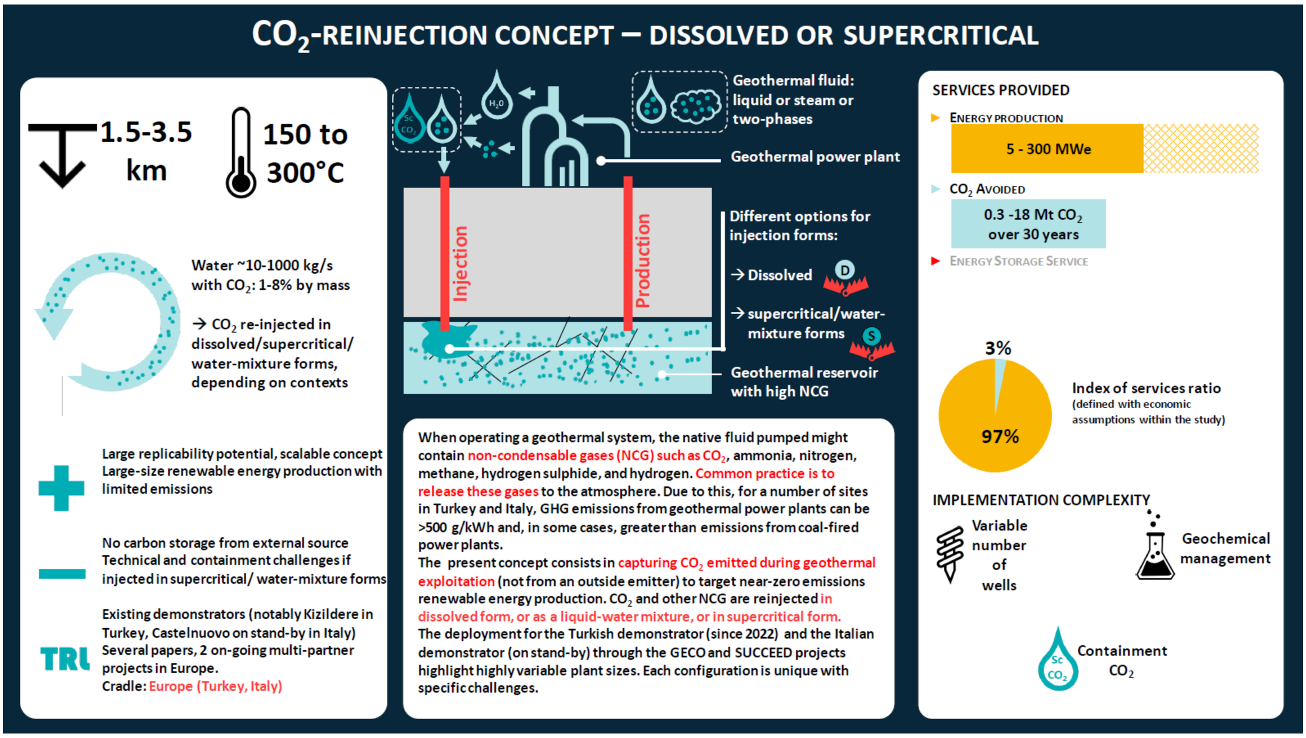

Figure 2: Infographic for the CO_2-reinjection concept

For comparison these concepts were also compared against a set of performance indicators that were generated by internal brainstorming. An excel spreadsheet populated with criteria (and sub-criteria) vs concept was produced with each sub-criteria being given a likert scale (1-5) score (5 best performance 1 is the least), a qualitative description and a colour coded flag (turquoise for a favourable argument; yellow for a nuanced argument and red for an unfavourable argument). An overview of the criteria, sub-criteria for selected concepts are shown with likert scoring in figure 3 and a higher level averaged score for the main criteria can be compared to a select number of concepts e.g. figure 4.

	CO_2-EGS	CPG	Heat mining with SC-CO_2 in gas/oil reservoirs	CPG-ES	Earth Battery - CO_2-BES/TES	Carbfix*-like concept	CO_2-reinjection concept	CLEAG-like concept	CO_2-DISSOLVED-like concept	Geothermal BECCS	CCS-driven concept	CCS with geothermal energy for capture process	Hybrid-energy systems	Synergetic dual use 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**	**3.5**	**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 CO_2 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	5	4	4
► The concept should be easily replicable considering underground conditions required.	3	4	2	3	3	2	4	3	5	5	2	3	2	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	3	5
► The concept should present a worldwide potential as high as possible for CO_2 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	4	5	5
INTEGRATION, MODULARITY & SCALABILITY	**3.3**	**3**	**4**	**2.7**	**3**	**4.3**	**3.7**	**4**	**4**	**4.3**	**3.7**	**3.7**	**4**	**3.3**	**3**
► Upstream requirements: If the concept requires external supply (e.g. CO_2 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	5	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	5	3	2
► The concept should be as scalable and adaptable as possible. ► Modularity and "Plug&play declination" would facilitate the integration.	2	2	3	2	1	4	3	5	4	4	3	3	2	3	3
PERCEPTION BY STAKEHOLDERS	**2**	**3**	**4**	**3**	**3**	**5**	**4**	**5**	**3**	**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	3
READINESS	**2**	**3**	**4**	**2**	**2**	**5**	**3**	**5**	**4**	**3**	**2**	**3**	**2**	**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	2	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**	**3.8**	**4**
► The surface footprint should be limited	5	5	5	5	4	5	5	5	5	4	5	5	5	5	5
► The water consumption should be limited	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
► The confinment of CO_2 should be guaranteed for CCS objective and safety issues (leakage)	1	3	5	2	3	5	4	4	4	4	4	3	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	3	4
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	**1**	**3**	**3**	**2.5**	**2.5**	**4**	**3.5**	**4.5**	**4.5**	**3.5**	**3.5**	**3.5**	**3.5**	**3**	**3.5**
► 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	2	2	4	4	5	5	4	4	4	4	3	4
► 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	3
CREDIBLE PATH TO COMMERCIALITY	**1.5**	**3**	**4.5**	**2**	**2.5**	**4**	**3**	**4**	**4**	**4**	**2.5**	**3.5**	**3**	**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	2	4	4
► The investment cost should be reasonable (high investment cost and initialization duration might be 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	4

Figure 3: Overview of all concepts and all key performance criteria – with corresponding ‘likert’ scale scoring and average (non-weighted)

	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

Figure 4: Main criteria performance indicators vs the concepts and averaged likert scale results (note these are unweighted averages)

Index to service ratio

In order to compare the overall contribution to energy production and CO_2 storage of the concepts an index to service ration was defined for this study.

- CO_2 storage expressed at Mt CO_2 stored over 30 years (assuming $30/tCO2)
- Levelized Cost of Energy (LCOE) for renewables (IEA, 2021) ~ 114 US$/Mwe.
- For concepts that produce thermal energy not converted to electricity 37US$/MWth is used (IEA).

The comparison of concepts according to their CO_2 storage capacity and power generation capacity are outlined on figure 1.

Many of the concepts described in this report are purely conceptual and based on a limited number of research ideas and concepts, however others are patented and at pilot or demonstration stage. These have been categorised by the level of research articles, patents, projects and also by first entry in the literature demonstrating the number of concepts envisaged over the past 20 years (Figure 5).

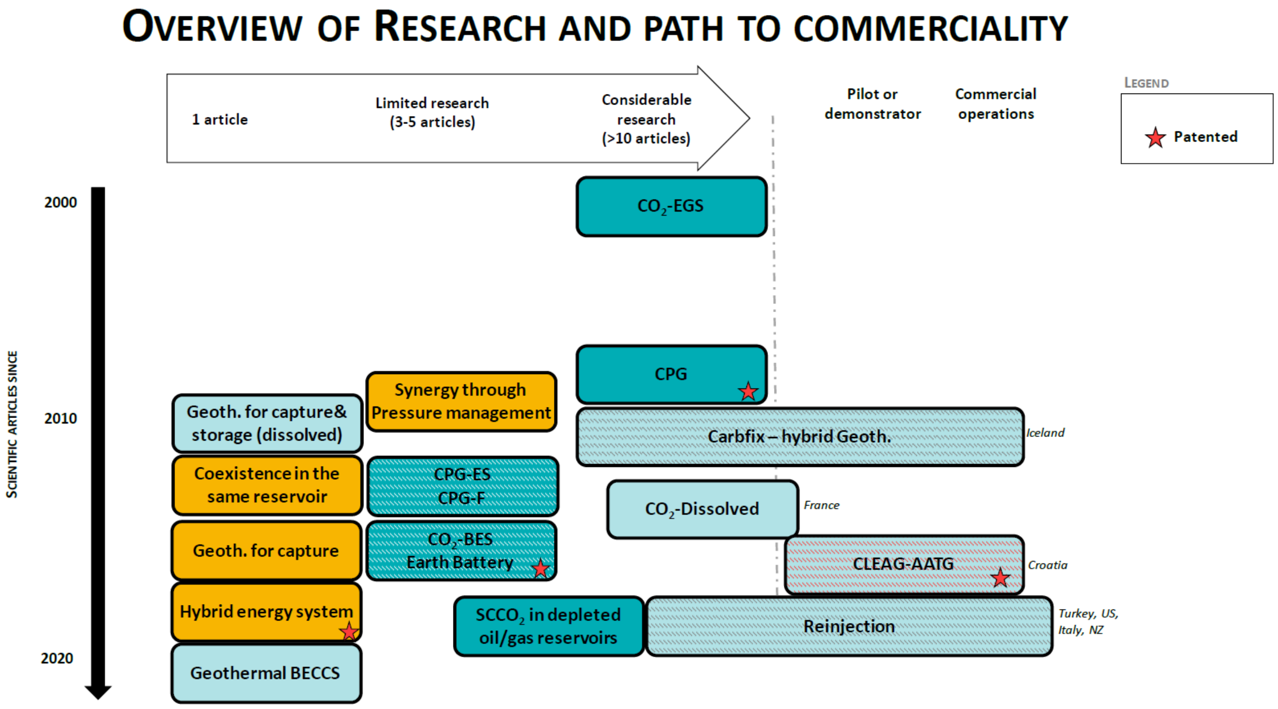

Figure 5: An overview of concepts according to numbers of papers written, time of introduction, patents and pilot projects.

Assessing potential areas for combined CO_2 storage and geothermal projects

To apply the combined use of geothermal energy and CO_2 storage requires the co-existence of favourable geological conditions likely to offer a geothermal resource and demonstrating the required properties for CO_2 storage, whilst also in relative close proximity to an industrial CO_2 emission source or within reach of a transportation network. Other factors are involved in guaranteeing the feasibility of a project and are acknowledged, however for a first level screening exercise publicly available data has been gathered that can be useful to screen technical criteria. These include data at global, continent and country scale, comprising:

- Subsurface data to identify and characterise appropriate reservoirs (geothermal resources and storage reservoirs)
- Data on industrial CO_2 emissions

Two case studies have been developed to combine the data to assess favourable areas these include a European study and a more detailed example for France. These provide examples for what is possible using publicly available data,In Europe the mapping exercise highlighted the following areas as good candidates for geothermal energy production and CO2 storage: the Paris Basin, France; the Pannonian Basin, Hungary and neighbouring countries; the eastern part of the North German Basin; the Molasse Basin, north of the European Alps; and the Campine Basin in Belgium and the Netherlands. For the French example data was combined from the AtlasGTH resource map (Maurel and Bonnefon, 2022; Caritg et al., 2018), an improved CO2STOP CCS potential map and data on industrial emitters from the French "Registre des Emissions" database. All these data have been included in a GIS, which are the basis of the map in figure 6.

The sedimentary basins of France are the main location for deep geothermal energy exploitation in hydrothermal systems and for CO2 storage (figure 6). Within the Paris and Marseille sedimentary basins, and their surroundings areas appear as the most suitable places to store CO2 as many industrial emitters are concentrated in these areas (figure 6). Whereas Lyon and its surroundings is not identified as having high CO2 storage potential, even though many emitters are present and a geothermal resource can be exploited.

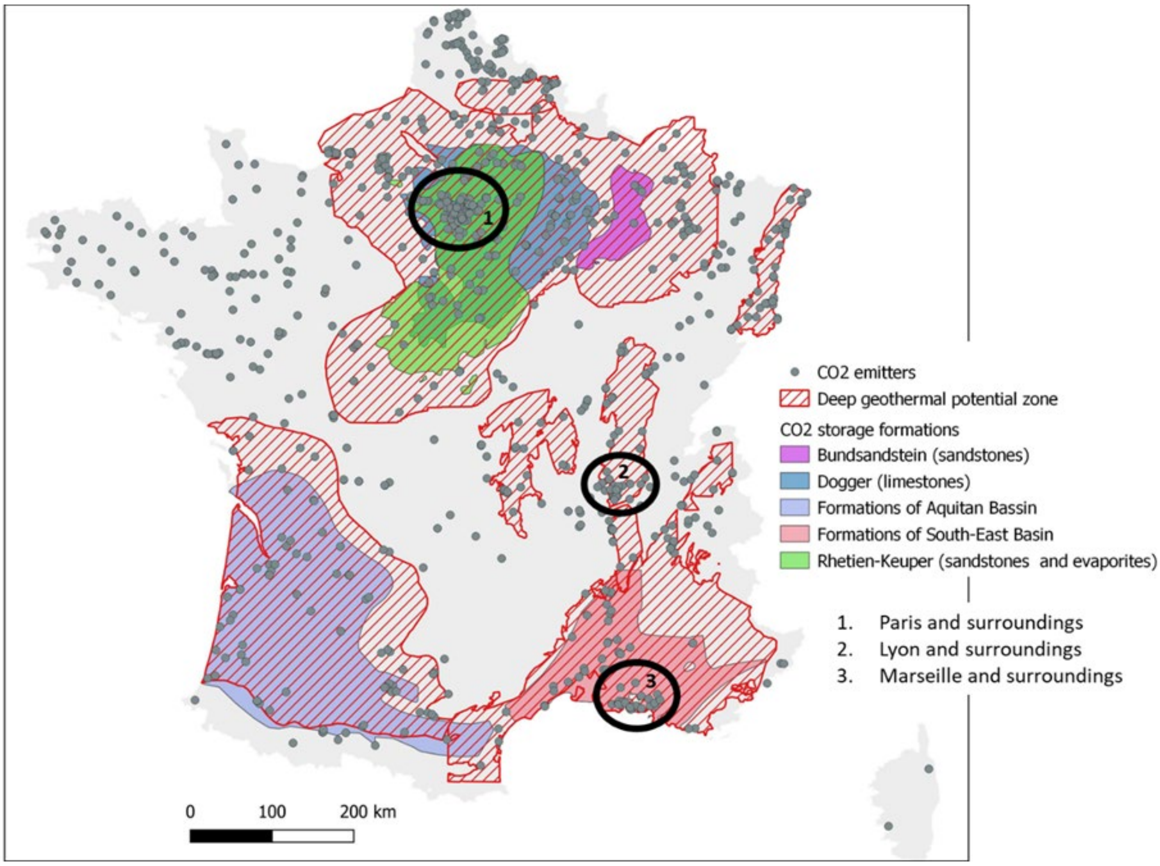

Figure 6: Map of France produced from combined data from the GeORG, CO_2STOP, and AtlasGTH projects in order to enable a first assessment of favourable areas for geothermal heat production and CO_2 storage. The map also includes the industrial CO_2 emitters.

Conclusions

Over the past 20 years there has been a growing body of work that explores the potential of utilising geothermal heat resources combined with some form of CCUS, either with CO_2 as a working fluid or CO_2 dissolved in water and with CO_2 sourced either from external emitters or directly sourced from geothermal fluids. The variety of concepts have been drawn together, described and categorised into this report from over 150 papers into 15 main concepts, and those that have reached demonstration or operating stage have been described in detail. A set of 17 comparable criteria under 7 themes have been carefully considered to allow for quick reference. It is intended that the work is a dispassionate and objective review.

From the ranking exercise the most ambitions 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. Whereas, 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, CO_2 re-injection). These concepts require high level of replicability if they are going to have a measurable environmental impact on reducing CO_2 emissions, but are potentially easier to manage permitting and gain social acceptance.

An evaluation of publicly available datasets has also been performed at various scales from global to country and regional scales to assess how useful they are at providing a first order screening tool to locate geographical areas that would suit both geothermal and CCS projects. Two examples are produced to demonstrate the type of methodology that might be employed to identify attractive regions of interest to implement specific concepts.

Expert Review

Seven expert reviewers provided comments on the study, each were thorough in their appraisal.

The report was deemed meticulous, detailed, comprehensive and a thorough review of methods and concepts that involve geothermal and CCS. With a clear conceptual and useful methodology for estimating performance of each method using expert witness/DELPHI approach.

Improvements suggested by the reviewers included:

- Adding an executive summary, a glossary, a meaningful set of conclusions and set of 'policy relevant' highlights. These were attended to by the authors.
- More critical analysis of the concepts including on project economics.
- Clarity over use of number of published articles and how this relates to readiness, the wording was altered to make sure these comments were addressed.
- Encouraged the use of TRLs. This was an issue that had been discussed in project meetings during the duration of the project and it was felt that the TRL status was both low and also potentially too complex to assign to a combined technology.
- Further clarification of the project objective regarding synergies when prospecting and exploring for CO2 storage sites and geothermal energy reservoirs. These were considered and added to the conclusion.
- Moving a borderline concept into the synergetic uses section, this was actioned by the authors.
- More discussion on what the comparison graphs and tables show – this will be addressed more fully in a separate scientific overview paper in preparation.
- Suggestion to classify into low-enthalpy and high-enthalpy geothermal which would help allocate concepts to different geological situations and geographical areas. It was felt that although some concepts could be categorised the majority would be hard to categorise in this way and other underground characteristics have been fully explored.
- Suggestion to add further resources to section 5.1.2 – this section was extended and improved in structure and increased content.
- General comments on layout, referencing and style – all these comments were addressed by the authors.

All comments were addressed either by adopting the comment, producing more work or by giving a reasoned response as to why not.

Recommendations

Funding for innovative concepts ought to be prioritised according to the potential for replicability and deployment potential.

In parallel with technical and scientific work, further legislative and policy action is needed to adapt local regulations when and where necessary to avoid administrative barriers in the development and later deployment phases of combined projects.

There is a lack of Life Cycle Analysis (LCA) for the whole chain (capture transport, injection, storage and geothermal energy production/exploitation) in most of the literature. It would be of interest to compare the LCA performance of a hybrid concept with that of pure geothermal use.

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.

Expand the case studies beyond Europe and include induced seismicity in the mapping criteria.

Incentivised public co-funding is necessary to see pilots studies to completion, for example funding of subsurface data acquisition with the results made available to the scientific community which may reduce initial investment of pre-feasibility phase.

The timing and manner of societal engagement is critical to success and acceptance, careful management of public education and engagement is necessary to prepare the ground for the adoption of novel and first of kind projects such as the combined use of geothermal and CCS projects.

Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS)

IEA/CON/22/283

by

BRGM

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Acknowledgement

Studying the ‘combined CCS and geothermal energy’ concepts is of particular interest in this period of energy and climatic crisis, where solutions must be found to open new routes toward a better energy management with limited CO_2 emissions. The timing of this report is perfect and we are grateful to IEAGHG for proposing this topic and, above all, for awarding our proposal and funding this study.

We are also grateful to IEAGHG for their availability for interesting scientific discussions and debates throughout this work.

The BRGM team

Christophe Kervevan (Coordinator)

Annick Loschetter, Rowena Stead, Chrystel Dezayes, Thomas Le Guénan

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Abbreviations

AATG	The company that develops CLEAG's first power plant in Draškovec, Croatia, since 2013
AFOLU	Agriculture, Forestry and Other Land Use
ATES	Aquifer Thermal Energy Storage
BES	Bulk Energy Storage
BECCS	Bio-Energy Carbon Capture and Storage
BTES	Boreholes Thermal Energy Storage
CAES	Compressed Air Energy Storage
CAES-A	CAES in Aquifers
CAES-C	CAES in Caverns
CAES-PM	CAES in Porous Media
CCES	Compressed CO_2 Energy Storage
CCES-A	CCES in Aquifers
CCES-PMCCES	CCES in Porous Media
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CLGS	Closed Loop Geothermal System
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
CLEAG	CloZEd Loop Energy AG, name of the company that developed the technology
CO_2-EGS	CO_2 – Enhanced/Engineered Geothermal System
CHP	Combined Heat and Power
CPG	CO_2 Plume Geothermal
CPG-BES	CO_2 Plume Geothermal – Bulk Energy Storage
CPG-ES	CO_2 Plume Geothermal with Energy Storage
CPG-F	CO_2 Plume Geothermal – Flexible (i.e. including Energy Storage, similar to CPG-ES)
DACCS	Direct Air Carbon Capture and Storage
DHN	District Heating Network
DOE	US Department of Energy (NETL)
EGEC	European Geothermal Energy Council
EGR	Enhanced Gas Recovery
EGS	Enhanced/Engineered Geothermal System
EOR	Enhanced Oil Recovery
ES	Energy Storage
GHG	GreenHouse Gas
HDR	Hot Dry Rock
HPT	High Pressure Turbine
IEA	International Energy Agency
IEA-GHG	International Energy Agency – Green House Gas
IGA	International Geothermal Association
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis/Assessment
LCOE	Levelized Cost Of Energy/Electricity
LHV	Low Heating Value
MTES	Mines Thermal Energy Storage
NETL	National Energy Technology Laboratory (DOE)
NCG	Non-Condensable Gas(es)
NZE	Net-Zero Emissions

ORC	Organic Rankine Cycle
$scCO_2$	Supercritical CO_2
TES	Thermal Energy Storage
TRL	Technology Readiness Level (1-9 scale)
UTES	Underground Thermal Energy Storage

If an abbreviation is only used once or restricted to just one part of the text, it is explained therein and does not figure in this table.

Glossary

This glossary is not intended to be exhaustive and stand-alone but is included as a first-step aid for the reader. In parallel and if additional details or terms are needed, the reader is invited to consult the two main reference glossaries used for the definitions given here, respectively for CCUS and geothermal terms:

- IEA CCUS handbook (page 116)
- Clean Air Task Force (CATF) Superhot Rock Energy Glossary: https://www.catf.us/superhot-rock/glossary/

Term	Definition	Source
Aquifer	A porous and permeable rock that contains groundwater. It should be noted that water contained in aquifers used for geothermal energy exploitation or CCS is generally non-drinking water, with mineral content over the drinking water thresholds, notably for salt (NaCl), and is generally referred to as “brine”. The terms “water” and “brine” are used interchangeably in the present report.	Authors and reviewers
Brine	A highly concentrated salty water.	IEA CCUS handbook
Caprock	Rock of very low permeability that acts as an upper seal to prevent fluid flow out of a reservoir	IEAGHG 2011-01
Closed loop	A geothermal circuit containing a subsurface working fluid that is heated in the reservoir without direct contact with rock pores and fractures. Instead, the subsurface working fluid stays inside a closed loop of deeply buried pipes that conduct Earth’s heat. Shallow, closed-loop geothermal systems have been operating for decades, and deep and next generation closed-loop geothermal projects are in development. The advantages of a deep, closed-loop geothermal circuit include: (a) no need for a geofluid (b) no need for the hot rock to be permeable, (c) all the introduced fluid could be recirculated, and (d) the ability to adapt methods and logic that already exist for shallow, closed-loop geothermal circuits.	CATF
Doublet (geothermal)	A set of 2 wells, one used for producing the geothermal fluid and the other for its reinjection	Authors and reviewers
Enthalpy (reservoir)	The measurement of energy or total heat in a thermodynamic system (Oxford English Dictionary). Enthalpy is used to relate the energy of a system, heat transfer and work done (Libretexts.Org, online). Geothermal systems can be low-, medium-, high- or super-high-enthalpy.	CATF
Geothermal (energy)	Geothermal: an adjective relating to heat within Earth.	CATF

	Geothermal energy: thermal energy that originates from a few metres to several kilometers beneath the Earth's surface. Geothermal energy is a clean, renewable source of energy throughout the daily cycle of power demand.	
Heat mining	This term is commonly used in the geothermal community to refer to the transfer of heat from the underground to the geothermal fluid. The heat is retrieved at surface through heat transfer and the fluid reinjected at lower temperature. The term "mining" might be misleading for broader audience, since it is usually used for a substance (and not for a heat transfer) that, once mined, is not available any more at the same location in the short term (while for geothermal energy exploitation, replenishment of heat takes about the same amount of time as you have spent extracting it).	Authors and reviewers
Hybrid concept / technology / use	These terms refer to concept/technology with combined objectives (underground carbon storage and geothermal energy production and/or storage).	Authors
Hybrid geothermal system	Hybrid geothermal systems or multi-system hybrids: systems that couple (a) two geothermal system types, such as engineered geothermal systems and advanced geothermal systems, or conventional hydrothermal systems, or (b) two different energy systems such as solar and geothermal, direct air capture and geothermal, hydrogen and geothermal, energy storage and geothermal, etc. These systems can be deployed in a variety of rock types.	CATF
Hybridization	In this report, the word "hybridization" refers to the combined search of two objectives, underground carbon dioxide storage and geothermal energy production and/or storage.	Authors
Injection well	Wells used to inject CO2 or other fluids	IEA CCUS handbook
Injectivity	The ability to inject CO2 (or another substance) into a reservoir at a required rate over time.	IEA CCUS handbook
Open loop	A geothermal circuit containing subsurface working fluid that is heated in the hydrothermal reservoir during direct contact with rock pores and fractures. Open-loop circuits currently operate in shallow, deep, hydrothermal, and engineered geothermal system types. The fluid ascends a production well and is used to work a heat or power device at Earth's surface. The fluid descends a reinjection well back into the hydrothermal reservoir rock, absorbs more heat, then recirculates to a production well. Open-loop circuits could operate in superhot rock geothermal plays. They may require large volumes of introduced fluid because some fluid may be lost into the hydrothermal reservoir during each fluid circulation.	CATF
Permeability	How easily a fluid can pass through a material.	IEA CCUS handbook
Porosity	The proportion of rock pores compared to the total rock volume.	IEA CCUS handbook

Production well	A well used to recover (extract) a liquid or gas resource from the subsurface. A production well can be for oil, natural gas, water or other resources.	IEA CCUS handbook
Saline aquifer	Porous and permeable sedimentary rocks that contain salty, non-potable water commonly known as brine.	IEA CCUS handbook
Storage vs. Sequestration	The terms storage and sequestration are frequently used interchangeably but it should be noted that some authors introduce a nuance between them: storage with a lifetime greater than 100,000 years is called sequestration, while temporary storage with a lifetime of less than 1000 years is referred to as storage (Scott et al., 2015). In the present report, we adopt the term storage, making the assumption that the storage lifetime is sufficient to be considered as permanent and valuable to tackle climate change.	Authors
Storage capacity	General definition: The estimated storable capacity of a resource. SRMS (Storage Resource Management System) definition: The estimated commercially storable quantity of CO_2 for a given resource/project.	IEA CCUS handbook
Supercritical state / CO_2	The state of CO_2 when it is at or above its critical temperature and critical pressure. a substance at a temperature and pressure where distinct liquid and gas phases do not exist. A substance at a temperature and pressure where distinct liquid and gas phases do not exist.	IEA CCUS handbook CATF
Thermal breakthrough	In a geothermal doublet, thermal breakthrough occurs when the cooling of the reservoir due to reinjection of colder water reaches the production well, with direct consequences on energy performances.	Authors
Working fluid	A fluid, whether a geofluid (naturally occurring brine, water, steam or supercritical fluid) or an introduced fluid (sourced externally due to insufficient geofluid), that is heated in natural or engineered hydrothermal reservoirs and in open-loop and closed-loop geothermal systems.	CATF (adapted)

Executive summary

In light of the current global energy crisis, caused by both geopolitical and physical issues (e.g. fossil fuel supply disruptions), and in a context of greater awareness of the emergency to ramp up our fight against climate change, the development of new renewable energy sources, as well as the abatement of CO_2 emissions, are of vital importance. From this perspective, the timing of the present study, which aims to review the current state of the art on technologies mutualizing geothermal energy production and Carbon Capture and Storage (CCS), is highly appropriate. In order to conduct this study, the work is divided into three main parts.

After two introductive chapters, the first part (Chapter 3) constitutes the core of the study. An extensive literature review was carried out of the concepts coupling geothermal energy production and CCS. The literature on this topic proved to be surprisingly rich, and over 150 publications were identified as pertinent and reviewed. The following classification is proposed to describe the concepts of greatest interest:

1) **Use of supercritical CO_2 as a heat vector for geothermal energy production** (Section 3.1)
   These concepts take advantage of the more favourable hydrodynamic properties of CO_2 vs. water (lower viscosity, higher compressibility and expandability) to increase substantially the heat extraction rate of a geothermal system. Five concepts are identified: CO_2 Plume Geothermal (CPG), CO_2-Enhanced/Engineered Geothermal System (CO_2-EGS), Heat Mining in former oil & gas reservoirs, CO_2 Plume Geothermal with Energy Storage/Flexible (CPG-ES/F), Earth Battery. They are mainly theoretical concepts at this stage and no pilot exists to date, despite CO_2-EOR and CO_2-EGR (which have similarities with parts of these concepts) being widely deployed for oil and gas recovery.

2) **Water-driven geothermal concepts with CO_2 injection/reinjection, generally dissolved in the geothermal brine** (Section 3.2)
   a) ***Injection of CO_2 emitted by an external source for CCS***
   b) ***Injection of CO_2 emitted by geothermal brine exploitation to achieve near-zero emissions in geothermal operations***

   In subcategory 2a, CCS is generally the primary objective, although in many cases the performance of heat extraction is higher than that of CO_2 storage, mainly because the maximum solubility of CO_2 in brine physically limits the amount of CO_2 that can be stored. Three concepts are identified: CO_2-DISSOLVED, Geothermal BECCS, and a CCS-driven concept to compensate additional energy demand for capture. Discussions are underway with French industrial companies interested in the CO_2-DISSOLVED concept, with a view to launching a future demonstration project.

   Subcategory 2b also comprises three concepts: CarbFix combined with geothermal heat extraction, CloZEd Loop Energy AG - CLEAG, and a CO_2-reinjection concept) In the first two, CO_2 is injected entirely dissolved in brine, whereas in the third concept, part of the CO_2 may also be injected as a supercritical phase. CO_2 storage constitutes a minor part of the service (a few percent at best). For these three concepts, pilots already are operational (CarbFix in Iceland) or about to start (CLEAG in Croatia, CO_2 reinjection in Italy and Turkey).

3) **Other synergetic uses with only slight hybridization** (Section 3.3)
In these cases, synergy is not achieved through the dual use of the geothermal fluid for CO_2 storage. The geothermal fluid and CO_2 are handled separately, but they both target the same reservoir. Three concepts are identified: CCS with improved efficiency in the capture process by using geothermal energy, synergy through dual non-competitive use in the same reservoir, and synergetic use through pressure management. The primary objective is CCS with estimated storage objectives of several tens or hundreds of megatons of CO_2 over a 30-year period. Geothermal energy recovery is beneficial to a much lesser extent, but may help the economics of these concepts.

4) **Other borderline concepts, out of the study scope** (Section 3.4).
These concepts, which do not fit the previous categories presented above, are introduced briefly for the sake of completeness.

Some of the concepts mentioned so far share similarities. In order to facilitate the global understanding of these hybrid uses of the underground, we present a synthesis based on infographics (Appendix 8.2.1), i.e. illustrations for each concept summarizing the key features, expected performance, and the underlying principles. With the help of these infographics, which all rely on the same symbols and page layout to facilitate comparison, the reader can conveniently and quickly obtain an overview (without having to read chapter 3).

The second part of this study (Chapter 4) focuses on providing an analysis grid and defining a screening methodology. For this purpose, seven Key Performance Indicators (KPIs) were developed addressing: ambitions and replicability; integration, modularity and scalability; perceptions by stakeholders; an overall readiness indicator capturing performance and safety; environmental risks and impacts; technical complexity and scientific challenges; and credibility of a path to commerciality. The KPI methodology uses indicators that include consideration of stakeholders and commercial elements. Collectively, the proposed set of robust criteria was used to classify concepts and, ultimately, to compare them in a quantitative way. We have found that conventional Technology Readiness Levels (TRL) are difficult to apply. This difficulty is due to the largely theoretical nature of most concepts, as well as heterogeneous TRLs and commercial maturity of essential technology components within any one given concept. The difficulties do not allow for a definitive system- or concept-level TRL assessment.

As a first step to evaluating the KPIs of the concepts, quantitative indicators or marks were assigned to each concept for a series of criteria. Adding up KPI marks to give an overall total is not considered objective, as already the weighting of each criteria may greatly differ according to the bibliographic reference as well as to the reader and his/her main interest. Instead, and in order to provide a global view of average KPIs for each of the concepts, the findings are summarized in a table displaying the criteria in rows and the concepts in columns (Appendix 8.1). As another convenient way of comparing the concepts among key criteria, such as amount of CO_2 stored, energy produced (heat or electricity), features of the underground and of the external CO_2 emitters, readiness of the concept, etc., a set of nine infographics including all the concepts was developed (Appendix 8.2.2).

Table 12 provides an overview of the scores assigned by the authors of this report, which, as mentioned above, can be debatable. It appears that 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. Note that, according to our evaluation, CO_2-EGS and CPG-ES have the lowest scores for ensuring CO_2 storage, which requires the inclusion of high-level monitoring procedures when setting up a first pilot to measure actual performance. In addition, the inclusion of large amounts of CO_2 requires that the CO_2 is effectively available, either from a nearby large industrial facility with high CO_2 emissions, or from an existing (or to be built) infrastructure that can deliver CO_2 on site. Although the former is by far the preferred option (the global CO_2 balance is much more favourable if CO_2 is not transported from a distant location), having a high-capacity storage site close to a large CO_2-emitting facility or hub places additional constraints on the feasibility of such a project.

Conversely, 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/AATG, CO_2 re-injection). Generally speaking, the lower the CO_2 content, the easier it will be to manage the permitting process and the operation of the plant itself, and probably also to gain social acceptance. These concepts, taken individually, will however have a much smaller impact on reducing CO_2 emissions on a global scale than the concepts involving CO_2 as a heat vector. Consequently, they require a relatively high level of replicability to have a measurable environmental impact on a regional or national scale.

The concepts described in this report rely on i) specific geological features of the underground, depending both on the type of geothermal energy targeted (deep, shallow, hydrothermal, fractured, high/medium/low temperature) and the use of CO_2 (heat vector in replacement of brine, or co-injected with brine and/or dissolved in brine); ii) the presence of a nearby external source of CO_2 (from an industrial site and/or a naturally CO_2-rich brine); and, for a few concepts, iii) the availability of an exploitable supplementary source of energy naturally contained in the geothermal brine (dissolved CH_4, for instance). Whatever the proven or claimed performance of a system, it is indispensable to estimate its potential in terms of deployment possibilities: a favourable CCS-geothermal system will have limited impact on the atmospheric carbon budget if it can only be implemented at one site featuring the requisite conditions. A less-efficient concept (in terms of amount of CO_2 stored and/or quantity of geothermal energy produced) that is widely deployable is of much greater interest.

To pave the way for future CCS-plus-geothermal energy resource analysis, **the third part of this study (Chapter 5)** provides examples of available data on geothermal resources, CO_2 storage potential, and location of industrial CO_2 sources. Worldwide mapping of favourable places for each of the concepts described in this report is beyond the scope of this study. Such maps, for example the CarbFix Atlas[1], are fundamentally dependent on the availability and quality of data. Major disparities are observed between areas that are well documented (e.g. North America or Western Europe) and others for which public information is scarce or inexistent to our knowledge (e.g. parts of Asia, most of the African continent). The way these data can be combined very much depends on the nature of the concept. For example, some need to be preferentially located close to an industrial facility emitting CO_2 (e.g. CO_2-DISSOLVED or geothermal-BECCS), whereas others, such as Direct Air Capture with geological CO_2 storage, do not. Two maps, one for France and one Europe, show information on geothermal resources, storage potential (for supercritical CO_2) and industrial CO_2 emitters. Although the map of Europe is less comprehensive than that of France concerning industrial emitters, such maps are useful for preliminary screening of several concepts considered in this report (categories 1, 2a, and 3).

[1] https://www.carbfix.com/atlas

1 Introduction and objectives

For several decades, it has been recognized that underground CO_2 storage and geothermal energy exploitation need to play a significant role to achieve carbon neutrality and to limit global warming. Among the range of solutions, geothermal energy and CO_2 Capture and Storage (CCS) constitute key pillars.

Large-scale geothermal facilities have been developed since over a hundred years for district heating and electricity production (the first use for electricity production was in 1904 at Larderello, Italy), with an ever-increasing installed capacity (see figures and mapping in section 2.2). CCS has seen unprecedented growth in recent years (see figures in section 2.3, Global CCS Institute, 2021). Nevertheless, considering the alarming predictions regarding global warning (IPCC, 2021), this growth is still insufficient and there remains a massive gap between today's deployment and the objectives to reduce global anthropogenic emissions to net zero by 2050 and meet the Paris Agreement targets.

Amongst the factors hindering deployment of these two technologies, CCS suffers from economic and commercial incentives for wider deployment, whereas geothermal energy, depending on the context, is not always sufficiently competitive. In addition to the economic barrier, other hurdles include: a lack of political support and awareness, concern over public acceptance (societal barrier), technical challenges, insufficient knowledge of favourable subsurface conditions (geological barriers), environmental risks and impacts, how to tackle "small" emitters or hard-to-abate industries (which would require adaptation of classic large-scale CCS, hubs and clusters infrastructure or smaller-scale regional solutions). These hurdles, except the latter, apply to both technologies, with generally a higher level for CCS than for geothermal activities.

A promising way of addressing certain barriers consists of integrating both objectives, namely geothermal energy production and CO_2 storage, into projects. Synergies can lead to cost benefits and additional sources of revenue (heat, electricity, energy storage, supply of CO_2-storage as an environmental product, etc.), which could be decisive for the deployment of CCS and, to a lesser extent, geothermal energy. Additionally, in some cases, the energy performance (and thus efficiency and financial return) of combined geothermal and CO_2 installations could be increased by the use of CO_2 as a heat vector or by synergistic exploitation. Considering the political, environmental and societal dimensions, the value of such integration is difficult to quantify, but worthy of debate.

A number of research initiatives have emerged in recent years that propose synergies between geothermal energy and CCS:

- Some propose the use of supercritical CO_2 as a geothermal heat vector, in hydrothermal reservoirs (CPG for CO_2 Plume Geothermal), in fractured rocks (CO_2-EGS for Engineered/Enhanced-Geothermal Systems), and in depleted oil/gas reservoirs.
- The hybridization in hydrothermal reservoirs may be extended to energy storage with CPG-BES (Bulk Energy Storage) or CPG-ES/F (Energy Storage / Flexible).
- Other concepts foresee injecting dissolved CO_2 in liquid water-dominated geothermal fluids. Two main origins are possible for the injected CO_2: from an external source (e.g. CO_2-DISSOLVED concepts, CO_2 from capture in bioenergy operations, i.e. geothermal-BECCS) or from CO_2 from the separation of non-condensable gases associated with production of geothermal fluids (CO_2 reinjection concepts, CarbFix-like concepts, CLEAG/AATG-like concept).
- And yet others simply propose co-existence of both modes of exploitation in the same reservoir, with at least some mutualization of data and infrastructures, and possibly also resulting in performance improvement through reservoir pressure management.

Aligning the ultimate dual objectives of renewable energy supply and CO_2 storage contributing to carbon neutrality, these hybrid uses arguably outperform most other solutions in terms of climate-change mitigation. The economic potential of CCS could also be significantly improved when combined with geothermal energy, compared to CCS alone. However, although the two activities can work in synergy, demonstration at real scale is still very limited.

The hybrid technologies combining CCS and geothermal energy exploitation differ in several ways: philosophy, target depths and temperatures, geological features, replicability potential, scale of application, quantity of CO_2 stored, energy performance, readiness level, etc. To date, little consistent work has been done to present an overview and compare the interest of the different hybrid concepts, depending on surface needs and underground characteristics. The objective of this study is to compile a panorama of these concepts and to analyse their characteristics.

After setting the scene with some background context (Chapter 2) presenting some key elements of geothermal energy and CCS, plus narratives for combining these technologies, the work is organized as follows:

- **Chapter 3** Features an analytical literature review of the various CCS, geothermal energy and combined concepts.
- **Chapter 4** Provides a set of characterization and KPIs for hybrid technologies in order to identify the (surface and subsurface) contexts that are most suitable for each concept and to give an overview and comparison of the main characteristics and logistical implications of the different concepts and a concise overview of their pros, cons and specificities.
- **Chapter 5:** Provides methodological guidance on how publicly available data can be combined to determine the most favourable areas to deploy a specific hybrid CCS-geothermal concept. The purpose here remains to establish a preliminary prefeasibility potential mapping based on technical criteria which is exemplified by two maps specifically designed as part of this study.

This study was funded by IEAGHG and carried out by BRGM.

2 Setting the scene

2.1 Global warming and energy challenges

The IPCC (2021) states that "observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities". The atmospheric CO_2 concentration has increased steadily from ~280 ppm in 1750 to 410 ppm in 2019. The increase of GHG concentrations in the atmosphere contributes to global warming (Figure 1). According to the IPCC, projected changes in extreme conditions (heatwaves, heavy precipitation, agricultural and ecological droughts) will increase in frequency and intensity with each additional increment of global warming. In order to limit detrimental consequences of human-induced global warming, it is necessary, by 2050, "to limit cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions".

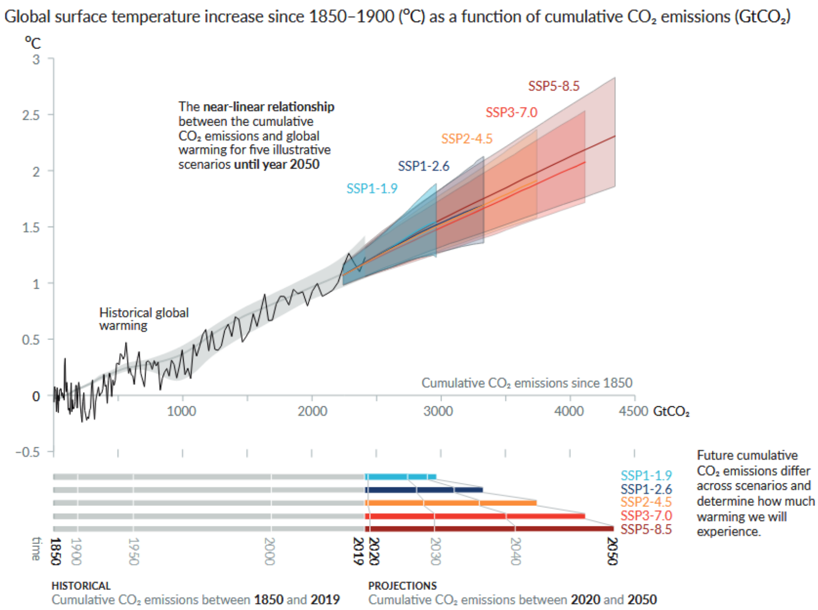


Figure 1. Near-linear relationship between cumulative CO_2 emissions and the increase in global surface temperature. Thin black line in the top panel corresponds to historical data from 1850 to 2019. "SSP-x" refers to different projection scenarios until year 2050 (IPCC, 2021).

According to the recent report of the IPCC concerning the mitigation of climate change (IPCC, 2022), "all global modelled pathways that limit warming to 1.5°C with no or limited overshoot, and those that limit warming to 2°C, involve rapid and deep and in most cases immediate GHG emission reductions in all sectors. Modelled mitigation strategies to achieve these reductions, including transitioning from fossil fuels without CCS to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand side measures and improving efficiency, reducing non-CO_2 emissions, and deploying carbon dioxide removal (CDR) methods to counterbalance residual GHG emissions".

Among the portfolio of solutions, the deployment of CCS and geothermal energy has a key role to play in contributing to existing and emerging environmental and energy challenges (Figure 2). In the following section, we present briefly both technological solutions independently to give an overview and current status of deployment. The main interests of hybridization is then explained.

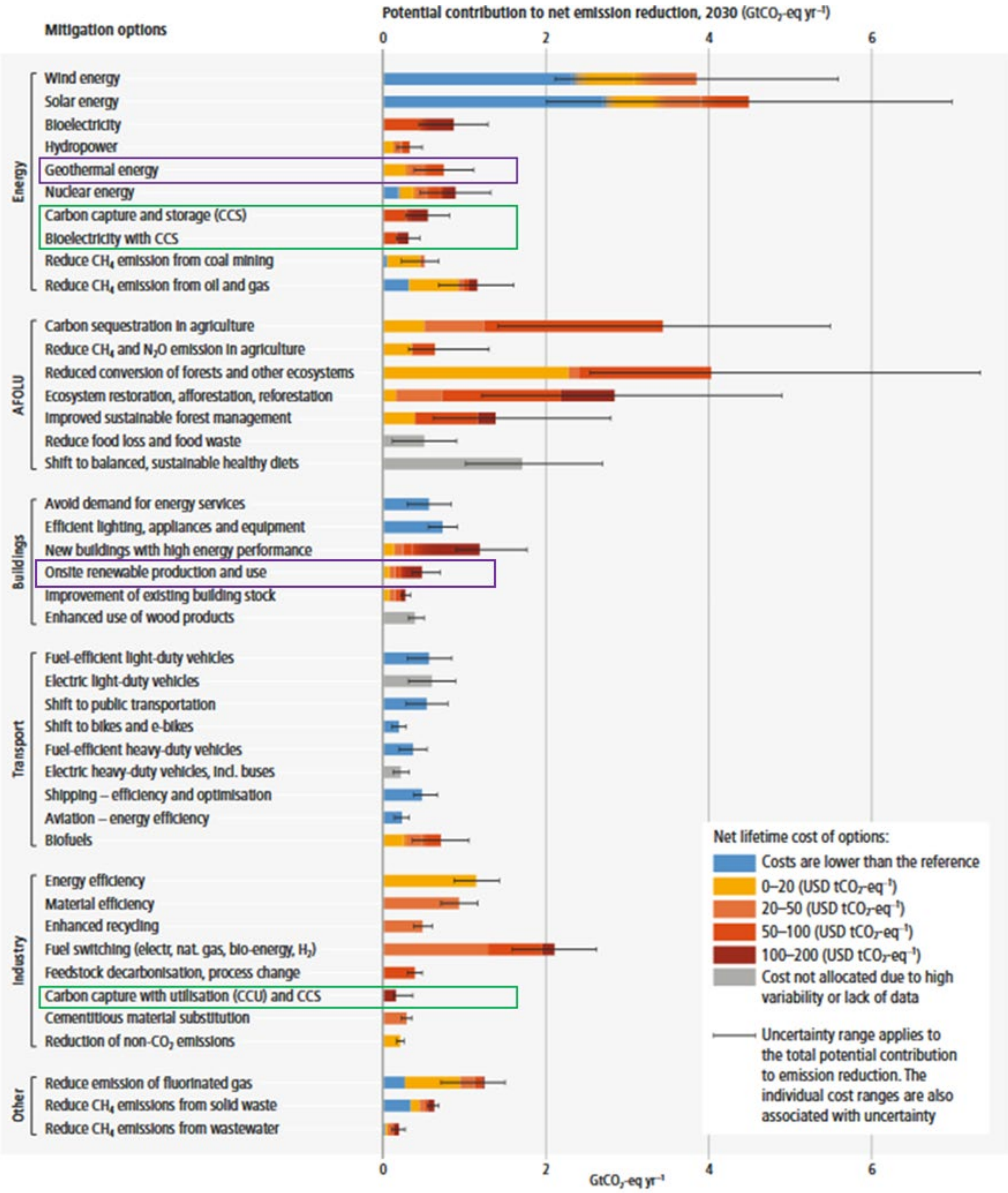


Figure 2. Overview of mitigation options and their estimated range of costs and potential in 2030 (AFOLU: agriculture, forestry and other land use) (IPCC, 2022). Violet frames shows expected contribution of geothermal energy and green frames expected contribution of CCS.

2.2 Geothermal energy

Geothermal energy is the energy stored beneath the surface of the earth in the form of heat. Its exploitation provides a renewable energy supply with limited carbon footprint for most cases. It can be produced by a variety of configurations that are based on the fact that underground temperatures increase with increasing depth[2]: i) for depths shallower than a few hundreds of metres, a ground source heat pump system (which extracts thermal energy directly from the ground or from aquifers) enables the supply of heating, cooling and/or hot water; ii) for intermediate depths between 500 m and up to 6 km – but more generally between

[2] https://www.egec.org/wp-content/uploads/2021/02/AC_EGEC_Brochure_3fold-and-pages_FINAL_preview-1.pdf , consulted September 23rd, 2022.

500 m and 3 km, subsurface reservoirs of water or hot rocks can be exploited for geothermal district heating and cooling; iii) for greater depths between 2 and 6 km (more likely 3 – 6 km in most geological contexts), steam or hot water can be piped to the surface to produce electricity, with capacities of individual geothermal wells ranging from 1 to 40 MWe. For intermediate to great depths, one can also discriminate different types of open-loop geothermal energy, depending on the geological context, and different types of closed-loop systems. Open-loop concepts describe the flow of reservoir fluids via wells to the surface, generally in liquid/vapour phases. Recent endeavours have also concentrated on developing supercritical geothermal resources. Closed-loop concepts exchange only heat across an impermeable interface (e.g. steel casing) between a fluid-saturated (or simply) hot rock and a secondary fluid circulating in a well that connects the (fluid-saturated) hot rock with energy conversion facilities (generally located at the surface).

When targeting a permeable and porous aquifer, the reservoir is referred to as a “hydrothermal system”. When targeting hot-rock formations with limited natural fluid flow and low permeability (e.g. Hot Dry Rock, HDR), it is necessary to identify natural fracture systems that enable the fluid to circulate between the injection and production wells or to create a reservoir through stimulation; this is referred to as an Enhanced/Engineered Geothermal System (EGS). However, in terms of underground contexts and project characteristics, the distinction is not always obvious and there is a continuum of configurations between two extreme scenarios, i.e. a virtually impermeable matrix with fluid circulation only in fractures (either a natural or induced fractured system) demanding a high-level of engineering to render subsurface fluid flow commercially viable vs. a homogeneous porous reservoir with high porosity and high permeability requiring a limited level of subsurface engineering.

In 2020, the total worldwide geothermal power capacity (Figure 3) rose to 15.7 GWe (EGEC, 2022), albeit with low global growth rates of 4% per annum over the last 10 years. In parallel, however, geothermal heating and cooling are becoming an important driver of new developments, with an increasing number of countries now looking to integrate geothermal solutions into their national energy strategy. Nonetheless, a massive gap persists between the current deployment rate and that needed to reduce global anthropogenic emissions to net zero. According to the IEA’s Net-Zero 2050 report (IEA, 2021), the geothermal electricity capacity should reach 126 GWe in 2050 (in comparison to the current 15 GWe), as indicated in Table 1.

Figure 3. Overview of geothermal power plants (ThinkGeoEnergy[3])

Table 1. Projected data for the Net-Zero Emissions by 2050 scenario for electrical capacity (CAAGR: Compound Average Annual Growth Rate) (IEA, 2021)

	Electrical Capacity (GW)					Shares (%)			CAAGR (%)	
	2019	2020	2030	2040	2050	2020	2030	2050	2020-2030	2020-2050
Total capacity	7 484	7 795	14 933	26 384	33 415	100	100	100	6.7	5.0
Renewables	2 707	2 994	10 293	20 732	26 568	38	69	80	13	7.5
Solar PV	603	737	4 956	10 980	14 458	9	33	43	21	10
Wind	623	737	3 101	6 525	8 265	9	21	25	15	8.4
Hydro	1 306	1 327	1 804	2 282	2 599	17	12	8	3.1	2.3
Bioenergy	153	171	297	534	640	2	2	2	5.7	4.5
of which BECCS	*-*	*-*	*28*	*125*	*152*	*-*	*0*	*0*	*n.a.*	*n.a.*
CSP	6	6	73	281	426	0	0	1	28	15
Geothermal	15	15	52	98	126	0	0	0	13	7.4
Marine	1	1	11	32	55	0	0	0	34	16
Nuclear	415	415	515	730	812	5	3	2	2.2	2.3
Hydrogen-based	-	-	139	1 455	1 867	-	1	6	n.a.	n.a.
Fossil fuels with CCUS	0	1	81	312	394	0	1	1	66	25
Coal with CCUS	0	1	53	182	222	0	0	1	59	22
Natural gas with CCUS	-	-	28	130	171	-	0	1	n.a.	n.a.
Unabated fossil fuels	4 351	4 368	3 320	1 151	677	56	22	2	-2.7	-6.0
Coal	2 124	2 117	1 192	432	158	27	8	0	-5.6	-8.3
Natural gas	1 788	1 829	1 950	679	495	23	13	1	0.6	-4.3
Oil	440	422	178	39	25	5	1	0	-8.3	-9.0
Battery storage	11	18	585	2 005	3 097	0	4	9	42	19

[3] https://www.thinkgeoenergy.com/map/ , consulted on September 23rd, 2022

2.3 Energy services from geothermal systems

The various services delivered by geothermal energy are considered briefly to provide contextual information relating to extraction systems and further comment on the scope of this report. The scope in the present study is to present available information on the kind of turbines and efficiencies, as reported in the original papers considered, not to add critical viewpoints or debate.

Geothermal energy is widely considered as a renewable resource and, in most cases, the carbon footprint is significantly less compared to fossil-fuel power plants. The following figures can be considered as approximate values:

- Coal-fired power plants come in a range of sizes from 100 MWe to 1000 MWe (IEA, 2012), with the less efficient smaller units used for niche applications and CHP. Newer plants for grid operation are large, typically perhaps 800-1000 MWe. If we consider an 800 MWe supercritical power plant with an efficiency 42% (LHV), the CO_2 emissions are around:

  178 kg CO_2/s for 800 MWe i.e. 0.22 kg CO_2/s/MWe
  19.1 kt CO_2/day for 800 MWe i.e.24 t CO_2/day/MWe
  5.6 Mt CO_2/year for 800 MWe i.e. 7 kt CO_2/year for 1MWe
  168 Mt CO_2 over 30 years for 800 MWe i.e. 0.21 Mt CO_2/MWe over 30y

- Orders of magnitude of CO_2 emissions for an 800 MWe coal-fired power plant correspond to CO_2 quantities that could be captured and stored in a large-scale CCS project (of the order of the Western Australia Gorgon project).
- For geothermal power plants however, its CO_2 footprint is highly variable: depending on the resource type and energy conversion technology, it can vary between 34 gCO_2/kWh and 1300 gCO_2/kWh (Fridriksson et al., 2017).

Producing electricity from geothermal heat presents several advantages over many other renewable forms of energy: electricity generated from variable renewables (such as wind or photovoltaic) requires integration into large network grids to offset the disadvantages due to their intermittent nature, whereas a geothermal plant, much like a bioenergy plant, provides consistent power regardless of the day/week/season. Thus it provides a stable and predictable contribution to the electricity grid.

The mechanism of power generation from geothermal reservoirs can be of two types: direct and indirect (Mohan et al., 2013; Adams et al., 2014; DiPippo, 2016; Singh et al., 2020):

- In the direct method, the geothermal fluid is directly used to drive the turbine to generate power (either in a dry flash plant or in single/double flash steam plant, see Figure 4). This method works better with special supercritical CO_2 turbine than with water turbine for a reservoir with low temperature because CO_2 has a higher compressibility and expandability than water. A technical challenge is the robustness of the turbines being suitable for handling the CO_2, and even more so when considering impurities (water traces, other impurities). The use of CO_2 (in particular supercritical CO_2) as the working fluid in power systems has been investigated for several decades and is a field of active enquiry (Lee and Sanchez, 2020).
- In the indirect method, a secondary fluid is used with a heat exchanger to extract the heat from the geothermal fluid. From a thermodynamic point of view, binary power plants generally use an Organic Rankine Cycle (ORC). Generating electricity in this manner is less efficient than using steam directly.

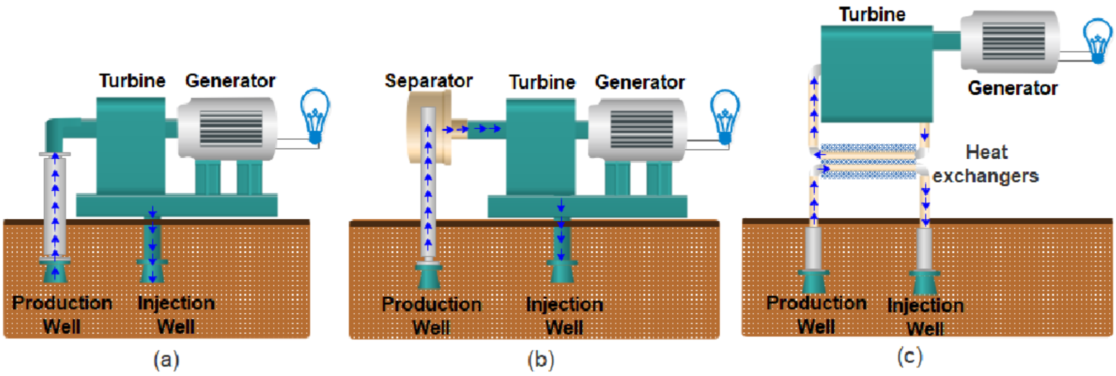


Figure 4. Illustration of different possible plants for power production with geothermal fluid. a. Dry steam plant. b. Flash steam plant. c. Binary power plant (Özkaraca, 2018)

The theoretical maximum mechanical work that can be extracted from heat energy is given by the Carnot efficiency: $1 - \frac{T_{reinjection}}{T_{reservoir}}$ where $T_{reinjection}$ is the reinjection temperature and $T_{reservoir}$ (K) is the fluid temperature at the output of the reservoir. In the example proposed by Randolph and Saar (2011b), with $T_{reservoir}$ = 373.15 K (100°C) and $T_{rejection}$ = 283 K (10°C), the Carnot efficiency is 24%. It increases as reservoir temperature increases (e.g. 33% for 150°C). It should be noted that the Rankine cycle is a practical cycle that has lower efficiency than the theoretical Carnot cycle. The Carnot efficiency is multiplied by the mechanical system utilization efficiency (e.g. value of 50% considered in Randolph and Saar, 2011b) to obtain the conversion efficiency).

The highest efficiencies can be achieved by providing combined heat and power (CHP), but this restricts the locations of facilities to sites near heat end-users (District Heating Network (DHN), industries).

In the literature, authors favour either direct or indirect methods for energy production, arguing either the higher efficiency of direct cycles or the robustness of indirect turbines to handle fluids with impurities.

With the introduction of renewable energies in the energy mix, an important challenge is the increased difficulty to adjust supply and demand. Balancing services need to be developed in order to accompany the increase of intermittent renewable energy sources in the energy mix, for example batteries and other electricity storage methods, demand response, etc. Underground energy technologies can play a role, not only through the production of relatively constant energy production, but also through balancing service. They can contribute to transform intermittent renewables into load-following power with carbon-neutral storage. Some concepts include services that contribute to balancing services:

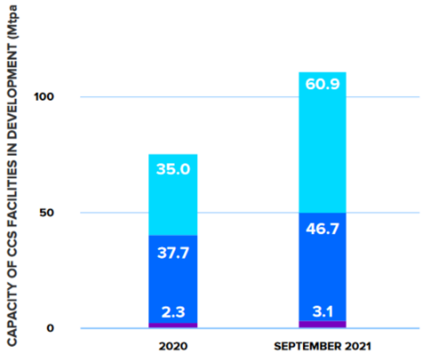
- A fluid can be compressed and stored underground (e.g. air, gaseous CO_2) when there is an excess of electricity. Energy stored during periods of low demand can then be released during peak-load periods: the fluid is expanded to produce electricity.
- In geothermal energy production, the gross energy production is largely superior to the net energy production due to the parasitic load required for fluid reinjection at depth. If the parasitic load is time-shifted during periods of high demand, the power capacity of the geothermal power plant can be temporarily increased. When the balance is opposite, energy can be retrieved from the grid to inject the fluid at depth. This requires the temporary storage of fluid (either at the surface, e.g. in a tank, or in a shallower aquifer). Although this theoretical concept is attractive, its practicability is questionable: i) storing fluids in tanks would require heavy infrastructure and investment; ii) storing fluids would induce significant geochemical challenges as precipitation reactions occur with cooling of the brines.

- These geochemical challenges are considerable in current geothermal operations and in practice define the temperature of fluid reinjection of each geothermal power plant.
- Underground reservoirs can also be used to store energy in the form of high temperature fluid (UTES: Underground Thermal Energy Storage).

These balancing services are included in the scope of the present study.

2.4 CCS

CCS is a critical climate-change mitigation and carbon removal solution that consists in capturing CO_2 from energy- or industrial-emission sources or directly from the air, and sequestering it permanently underground. Emissions into the atmosphere are therefore avoided or CO_2 is removed from the atmosphere. The idea of capturing CO_2 to prevent its release into the atmosphere was first suggested in the 1970s. The first projects emerged with the primary objective of boosting oil recovery (EOR – Enhanced Oil Recovery) and CO_2-EOR has played a role in advancing the deployment of CO_2 storage in a climate-change-mitigation context. The world's first dedicated industrial CO_2 storage project was launched in 1996 at the offshore Sleipner Field in Norway, where it has since been demonstrated that CO_2 can be injected, at a rate up to ~1 Mt/year per well, and safely stored in deep saline aquifers (mainly sandstone). As highlighted in Figure 5, the capacity of projects in development is growing significantly, reaching a potential of 111 Mt/year in 2021 and 244 Mt/year in 2022, representing an increase of 44% over the past 12 months (Global CCS Institute, 2021 and 2022).



	OPERATIONAL	IN CONSTRUCTION	ADVANCED DEVELOPMENT	EARLY DEVELOPMENT	OPERATION SUSPENDED	TOTAL
Number of facilities	27	4	58	44	2	135
Capture capacity (Mtpa)	36.6	3.1	46.7	60.9	2.1	149.3

Figure 5. Top: Capacity of CCS facilities in development (Mt/y). Violet: In construction; dark blue: advanced development; light blue: early development. Bottom: Commercial CCS facilities in September 2021 (Global CCS Institute, 2021)

A review of the main operational CCS projects is available (see Appendix 5 of the Global CCS Institute, 2021):

- Sleipner (Norway, ~1 Mt/y, operational since 1996),
- Snøhvit (Norway, ~0.7 Mt/y, operational since 2008),
- Quest (Canada, ~1.2 Mt/y, operational since 2015),
- Illinois (US, up to 1 Mt/y, operational since 2017),
- Gorgon (Australia, up to 4 Mt/y, operational since 2019),
- Qatar (2.2 Mt/y, operational since 2019).

Figure 6 presents a worldwide overview (in 2021) of CCS facilities including commercial, in development, and suspended. It should be noted that many operational large-scale CCS projects worldwide are based on EOR.

Figure 6. Panorama of CCS operations (Global CCS Institute, 2021)

Despite the unprecedented growth seen in recent years, the deployment of full-scale storage projects is way behind the pace needed to contribute significantly to meeting the net zero objectives and the Paris Agreement targets (e.g. Snæbjörnsdóttir et al., 2020; Global CCS Institute, 2021).

According to the IEA's Net-Zero 2050 report, the electrical capacity of fossil fuels with CCUS (Carbon dioxide Capture, Utilization and Storage) should reach 394 GWe in 2050 (in comparison to the current 1 GWe already installed), see Table 1.

According to the IPCC (2022), CCS has also to play a role through carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions and to manage the global temperature overshoot. CDR refers to the removal of CO_2 from the atmosphere by deliberate human activities and permanent storage in geological, terrestrial, or ocean reservoirs, or in products. "Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods" (IPCC, 2022). Other CDR routes under development include CO_2 captured directly from the atmosphere or from biomass, and then combined with CCS (respectively DACCS – Direct Air CCS and BECCS – Bio-Energy CCS) (IPCC, 2022).

2.5 Properties of CO_2 and use of CO_2 as a heat vector

Carbon dioxide is a gas that is naturally present in the air at standard temperature and pressure. At depth, when both temperature and pressure increase above the critical point for CO_2 (31.0 °C, 7.4 MPa), CO_2 transitions to a supercritical phase (see Figure 7): it behaves like a gas (with low viscosity) but has the density of a liquid. In order to reach supercritical conditions at depth, local mean temperature and pressure conditions must be above 31°C and 7.4 MPa. Depending on the site, and notably on the geothermal gradient, these conditions are generally met at depths greater than 800 m in areas with an average geothermal gradient around 30°C/km, and deeper for areas with lower geothermal gradients (see Figure 8).

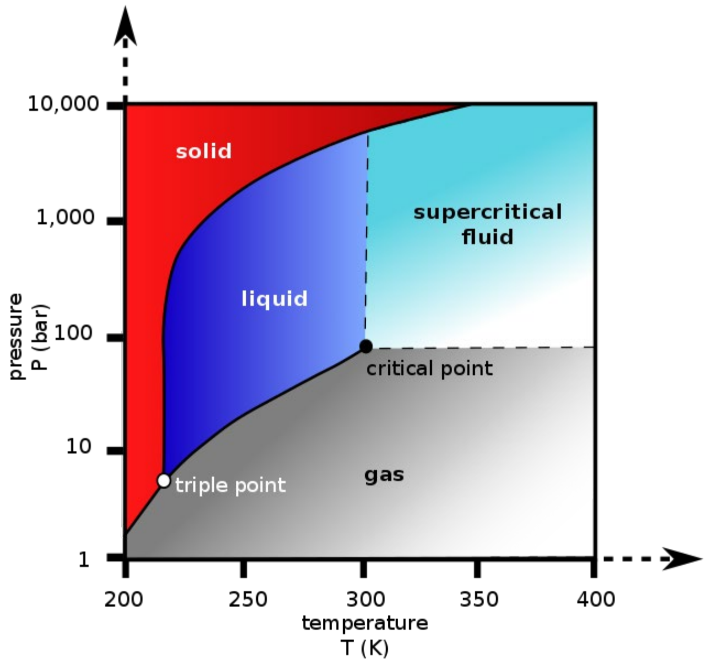


Figure 7. Carbon dioxide pressure-temperature phase diagram (Wikipedia)

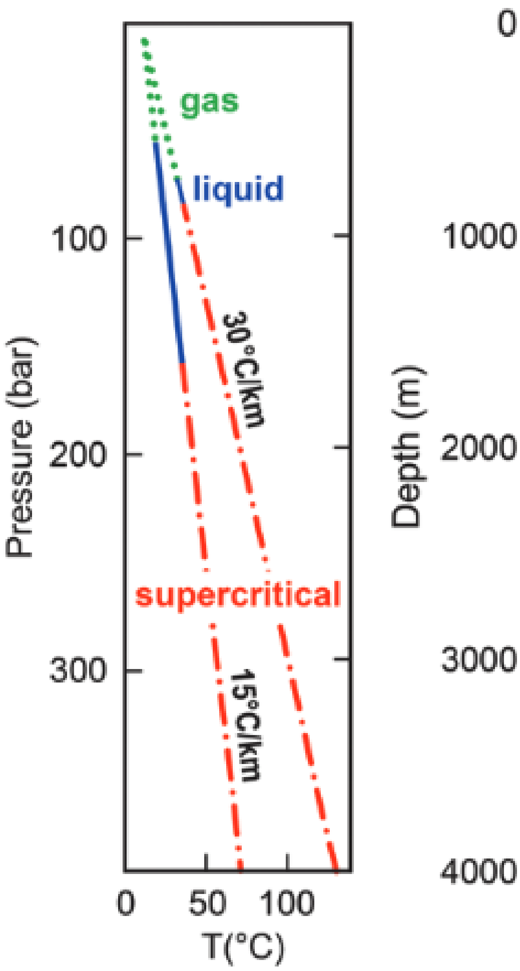


Figure 8. Phase behaviour of CO_2 as a function of temperature and pressure for two geothermal gradients (Benson and Cole, 2008)

Compared to water, CO_2 is more compressible and expandable (its density varies considerably with temperature and pressure), as illustrated in Figure 9 and Table 2.

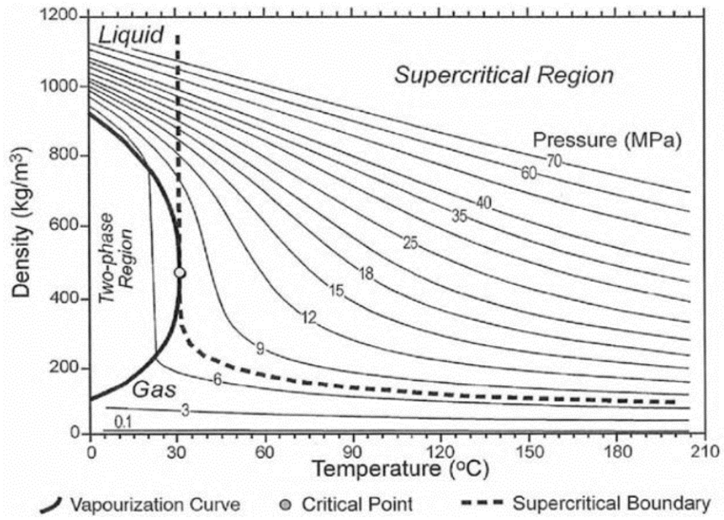


Figure 9. Variation of carbon dioxide density with temperature and pressure (Onyebuchi et al., 2018, reproduced from Global CCS Institute)

Table 2. Examples of density, compressibility, expansivity of CO_2 and water at 20 and 200°C, at 100 and 500 bars (Pruess, 2006)

Density, compressibility, and expansivity of CO_2 and water at selected (T, P)-conditions

		CO_2			Water		
T (°C)	P (bar)	ρ (kg m^{-3})	Compressibility (Pa^{-1})	Expansivity (°C^{-1})	ρ (kg m^{-3})	Compressibility (Pa^{-1})	Expansivity (°C^{-1})
20	100	856.251	1.490×10^{-8}	8.607×10^{-3}	1001.76	3.489×10^{-10}	1.944×10^{-4}
	500	1048.77	2.484×10^{-9}	2.696×10^{-3}	1015.94	3.538×10^{-10}	1.448×10^{-4}
200	100	122.184	1.076×10^{-7}	3.036×10^{-3}	870.798	8.377×10^{-10}	1.321×10^{-3}
	500	581.322	1.274×10^{-8}	3.172×10^{-3}	900.990	8.668×10^{-10}	1.077×10^{-3}

The advantages of using supercritical CO_2 as a heat vector for EGS (rather than water/H_2O) have been highlighted by Brown (2000), and then further discussed by numerous authors, either for CPG or EGS. Olasolo et al. (2018) summarize the main comparative features between CO_2 and water as geothermal working fluids (Table 3).

Table 3. Comparison of water and CO_2 as working fluids for geothermal heat mining. Properties considered as favourable are shown in bold (Olasolo et al., 2018)

FLUID PROPERTIES	CO_2	H_2O
Chemical	**Not an ionic dissolution product. No mineral dissolution/ precipitation problems.**	An ionic dissolution product. Serious problems of mineral dissolution/ precipitation.
Fluid circulation in wells	**High compressible and expandable.**	Low compressibility. Moderate expandability.
Ease of flow in the geothermal reservoir	**Low viscosity** & density.	High viscosity and **density**.
Heat transmission	Low specific heat level.	**High specific heat level.**
Fluid losses	**Could result in beneficial geological storage of CO_2.**	A hindrance for the development of geothermal reservoirs. Costly.

Fluid circulation in the reservoir

CO_2 has favourably a lower viscosity than water, thus increasing its mobility. However, CO_2 has unfavourably a lower density, which requires larger wellbore diameters as mass flow is important for geothermal energy conversion at the surface.

The controlling parameter for CO_2 circulation in the reservoir is the ratio of density vs. viscosity. Water/brine has limited expansivity/compressibility (density remains relatively constant) and water viscosity varies with temperature, which yields a density/viscosity ratio that increases with temperature due to viscosity decrease (Figure 10, on the right). For CO_2, the combined evolution of density and viscosity yields more complex variations of the ratio (Figure 10, on the left). For most cases, however, the ratio is superior for CO_2 compared to water.

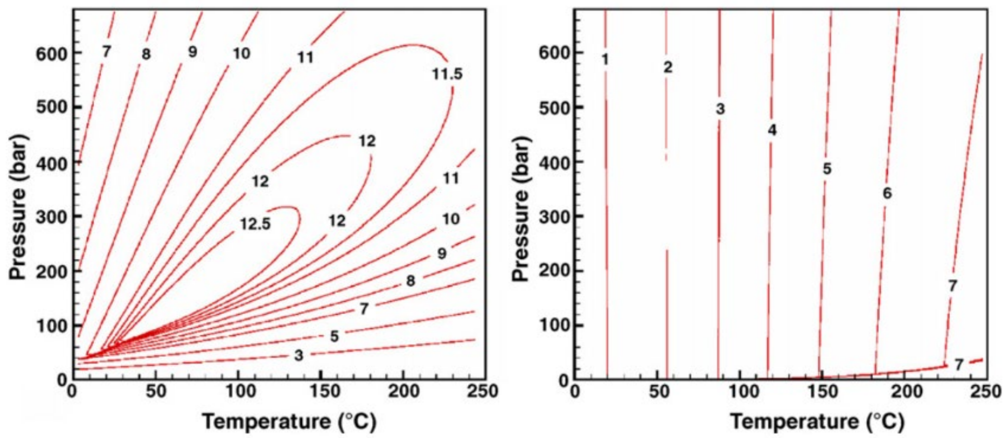


Figure 10. Ratio of fluid density to viscosity (units 10^6 s.m^{-2}) for CO_2 (left) and water (right) (Pruess, 2006)

Thermosiphon effect

CO_2 has high expansivity that will generate a large density difference between cold CO_2 (dense, heavy) in the injection well and hot CO_2 (less dense, light) in the production well (example in the case-study of Brown, 2000: quoting a density of about 0.96 in the injection well and about 0.39 in the production well). This provides a significant favourable buoyancy force that reduces the power consumption for circulating and pumping compared to a comparable water-based HDR system.

Heat mining
The other influential parameter is the mass heat capacity (kJ/K/kg). At constant pressure, it corresponds to the partial derivative of enthalpy (kJ/kg) with respect to temperature. Enthalpies are represented in Figure 11 for CO_2 and water. CO_2 has a mass capacity lower than that of water, which is detrimental for heat mining. However, for most situations, this effect is largely offset by achieving higher extraction rates for CO_2 compared to water due to its greater mobility (viscosity).

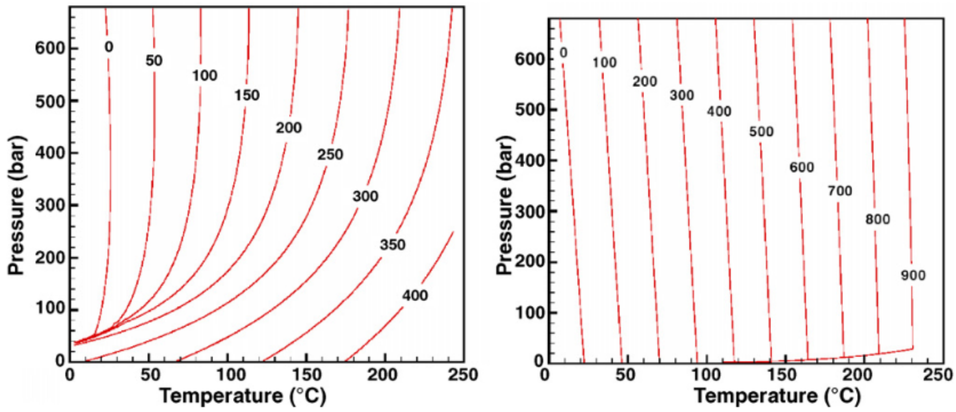


Figure 11. Enthalpy (units kJ/kg) for CO_2 (left) and water (right) (Pruess, 2006)

Performance dependent on pressure, temperature and geological conditions
The fact that density, viscosity and enthalpy evolve differently as a function of pressure and temperature for CO_2 and water explains the very different and sometimes apparently contradictory conclusions obtained by various authors when comparing the efficiency of CO_2 and water for heat mining. For most configurations found in the literature, CO_2 outperforms water as a heat vector, by a factor of 1.5 to 3. However, in some contexts, water might be more efficient than CO_2 (Olasolo et al., 2018). For example, for highly permeable formations, the lower viscosity of water is not a significant hurdle and so the advantage of using CO_2 becomes less significant (Randolph and Saar, 2011b).

Chemistry
From a conceptual viewpoint, supercritical CO_2 is not a universal solvent, unlike water. When CO_2 is used as a heat vector, issues related to mineral dissolution or precipitation are thus likely to be reduced. The inability of supercritical CO_2 to dissolve and transport mineral species to the well and to the surface equipment would reduce scaling issues. Some authors state that continuous operation of a CO_2-HDR system would be expected "to produce a rather dry CO_2 stream that would not pose corrosion problems for production wells" (Pruess and Azaroual, 2006).

However, in the field, theoretical considerations are likely to be counterbalanced by the reality of operations. In subsurface systems, a certain interface is expected between the CO_2 and the reservoir brine/moisture (even if residual). At such occurrences, water/moisture may be dissolved into the supercritical CO_2, which could induce two phenomena:

- a drying process and the associated precipitation of minerals (especially evaporite salts) at the interface between the two phases, which may eventually reduce the porosity and permeability, and thus the injectivity (e.g. Smith et al., 2022).
- in porous sedimentary rock where it is possible to sequester CO_2, it is unlikely that dry CO_2 would ever be produced. The transport of water vapour by the supercritical CO_2 may wet the stream, the vapour would eventually condensate into an acidic

solution in the well and on the surface equipment, and this may lead to serious corrosion problems.

2.6 Properties of CO_2 and implications for efficient and safe CO_2 storage

The terms storage and sequestration are frequently used interchangeably but it should be noted that some authors introduce a nuance between them: storage with a lifetime greater than 100,000 years is called sequestration, while temporary storage with a lifetime of less than 1000 years is referred to as storage (Scott et al., 2015). According to Scott et al. (2015), temporary storage is inefficient and "defers an intergenerational problem". In the present report, we adopt the term storage, making the assumption that the storage lifetime is sufficient to be considered as permanent and valuable to tackle climate change.

As formulated by IEAGHG (2009), the fundamental requirements of CO_2 storage are: 1) capacity to store the intended volume of CO_2 over the lifetime of the operation, 2) injectivity, to accept/take CO_2 at the rate that is supplied from the emitter(s), and 3) containment, to ensure that CO_2 will not migrate and/or leak out of the storage unit. A large amount of work on characterizing and qualifying storage sites has been done and is summarized in DOE/NETL (2017).

Under typical reservoir conditions, the density of CO_2 is lower than that of mineralized water, and CO_2 will thus migrate upwards due to buoyancy effect. Thus, the formation should be overlain by a sufficiently impermeable caprock to contain the CO_2. A structural concave-down geometry is generally favoured to control lateral migration. In any case, guaranteeing and demonstrating the containment of CO_2 underground is an important prerequisite for both objectives: contribution to global warming mitigation and short-term risks and impacts management. Different trapping mechanisms come into play (e.g. Kazemifar, 2022):

- Structural/stratigraphic trapping;
- Residual or capillary trapping refers to the immobilization of CO_2 within the pore spaces due to the action of surface tension forces between the injected CO_2 phase and the resident brine phase;
- Solubility or dissolution trapping: dissolution in the resident brine removes buoyant CO_2 and results in a denser fluid that tends to sink rather than rise, and hence represents a lower risk of leakage;
- Mineral trapping eventually occurs due to chemical reactions between CO_2 and alkaline minerals in the brine phase or formation rocks, which results in precipitation of CO_2 as solid carbonate minerals.

The ratio of the different trapping mechanisms depends on:

- Duration since injection: with time, CO_2 tends to dissolve and mineralize, thus progressively reducing the associated risks of leakage (Figure 12).
- Form of the CO_2 injected: when injected in dissolved form, the first two trapping mechanisms do not apply (structural/stratigraphic and residual/capillary).
- The geological conditions, which influence the degree of capillary trapping, dissolution and mineral trapping.

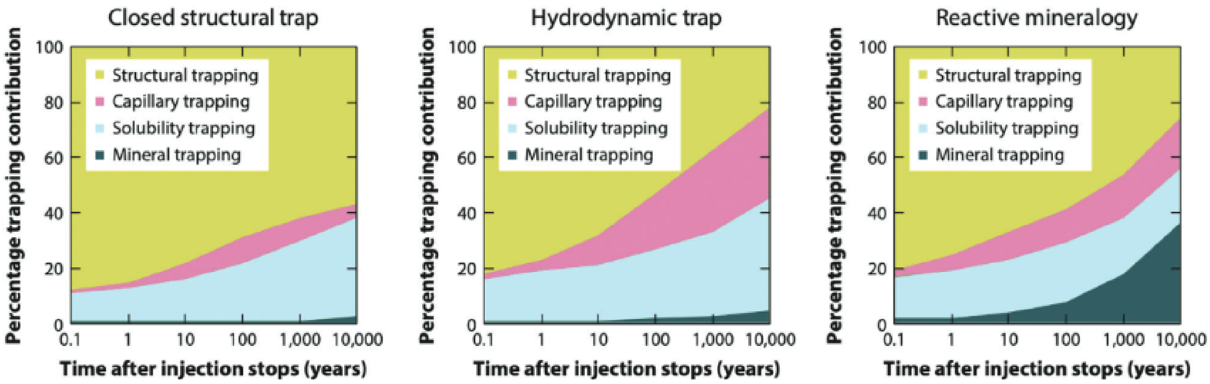


Figure 12. Illustration of trapping mechanisms and their evolution over time (Kazemifar, 2022)

In the context of geothermal energy, the fluid produced is usually reinjected in the same formation in order to maintain pressure. If the geothermal fluid comes from an external source (as CO_2), then not all the fluid injected can be produced back. Depending on the geological context, it might be necessary to compensate the fluid losses in order to maintain the pressure and performance of operations. This is particularly true in some EGS contexts (e.g. Hot Dry Rocks – HDR). If water is used as a heat vector, water loss in the reservoir is a drawback because it increases the demand on make-up water resources. For CO_2, as highlighted by numerous authors to promote hybrid concepts like CO_2-EGS, loss can be seen as beneficial since it will require additional CO_2 injection during operations, thus contributing even more to CO_2 storage. Nevertheless, this rosy picture should be nuanced by several points: i) in order to be considered as valuable for the CCS objective (very long term containment) and to guarantee safety (no leakage), it should be demonstrated that the CO_2 remains trapped over time; ii) this requires rigorous risk analysis and modelling, additional monitoring, and thus represents additional complexity and costs.
In addition to containment, other important concerns are pressure increase in the reservoir, possible seismic consequences and geo-mechanical deformations.

2.7 Solubility of CO_2: implication for solubility trapping and heat mining with CO_2 dissolved in water/brine

The solubility of CO_2 depends on pressure, temperature, and dissolved mineral content in brine.

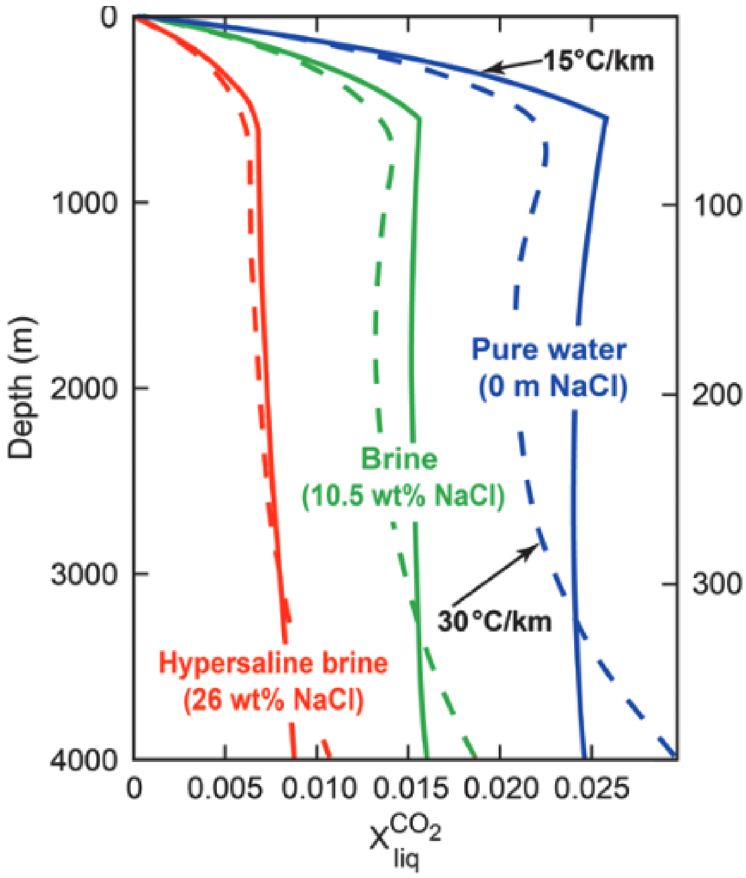


Figure 13. Solubility (mole fraction, ×) of CO_2 in a NaCl solution as a function of depth and salinity for two geothermal gradients. A pure-water system can dissolve 5 times more CO_2 than a hypersaline brine (0.01 in mole fraction corresponds to 2.4% by weight) (Benson and Cole, 2008)

The ratio of solubility trapping will thus depend on the geothermal gradient, depth and salinity, as illustrated in Figure 13. When using brine for geothermal extraction with injection of CO_2 in the dissolved form, the maximal quantity of CO_2 that can be dissolved in a given quantity of brine will be constrained by the CO_2 solubility under the respective pressure and temperature conditions and the composition of the brine.

2.8 Interest of hybridization

The interest of hybridization, in the general sense, is conceptually justified as follows:

- Better efficiency: as mentioned in section 2.5, the use of CO_2 as a heat vector could improve the performance of heat mining.
- Economic: both geothermal energy exploitation and CCS are relatively expensive (see Figure 2). Mutualization of data exploration, infrastructure, operational management, fluid exploitation for storage and solutions addressing energy challenges optimize these costs. The economic viability of CO_2 storage is a critical challenge for large-scale implementation of the technology. Energy extraction in conjunction with storage would improve the economic performance.
- Optimization of underground resources: certain forms of heat mining and CO_2 storage require certain similar geological features (e.g. high porosity and sufficient permeability) but temperature-wise, the targets are opposite. It should be noted that in many CCS projects, the permeability should not be too high, which favours capillary trapping. Rather than competition between various uses of the same resource, synergetic use should be sought.

2.9 Scope of the study

In the present study, we investigate the concepts, irrespective of their technology readiness, that combine the following features: CO_2 storage and geothermal energy supply (electricity, heat) or energy services, such as energy storage (thermal energy, electricity).

The CO_2 storage and geothermal energy concepts that are considered here show at least one of the following:

- share CO_2 as a fluid that circulates through a reservoir and not only extracts heat but is also stored;
- occur in reservoirs where geothermal energy extraction and CO_2 storage interact indirectly via pressure perturbations;
- use shared subsurface installations such as wells;
- use geothermal energy converted at the surface to electricity or heat for meeting energy needs in CO_2-capture facilities.

Concepts considered out of scope of this study are so-called “closed loop” systems, which have undergone considerable research and applications in ground source heat pump applications (Rieberer, 2005) and, more recently, in connection with so-called advanced geothermal systems (for a recent summary see, for example, Malek et al., 2022). Here CO_2 circulates as a heat exchanger fluid underground through pipes, wells or other geometries, and is isolated either by steel, ceramics or specially designed fluids that form a fully impermeable mud cake around wells, from directly interfacing with rock or connate geothermal fluids.

3 Literature review on concepts and projects combining geothermal energy use and CCS

In order to facilitate and contribute to the deployment of geothermal energy and CCS, many hybrid solutions have been proposed in recent years. The main concepts are grouped into four categories in this study:

- concepts that use supercritical CO_2 as a heat vector that extracts heat from a subsurface reservoir and where CO_2 has been sourced from a capture facility at the surface;
- concepts where geothermal energy is produced with water-dominated fluid, and where CO_2 is co-injected with water (generally in the dissolved form);
- concepts where the hybridization between geothermal energy production and CCS is less (both operations occur in reservoirs where geothermal energy extraction and CO_2 storage interacts indirectly via pressure perturbations, or use shared subsurface installations such as wells, or use geothermal energy converted on surface to electricity or heat for meeting energy needs in CO_2-capture facilities);
- concepts that are borderline to the present study, introduced briefly for the sake of covering the entire scope.

This chapter presents a literature review of these main concepts. For each concept we follow the same structure: first a description of the concept and main claims as found in the reviewed papers. Then, a table presenting the main characteristics of the concepts. Finally, we present some subjective critical considerations of the concepts. The comparison of performance on multiple criteria for all the presented concepts is presented in the accompanying spreadsheet. The method of performance evaluation is presented in detail in the next chapter.

3.1 Use of supercritical CO_2 as a heat vector for geothermal power plants

An overview of the different geothermal systems and their suitability for hybridization with CO_2 as a heat vector are given by Zhang et al. (2014) and Singh et al. (2020). Good candidates include:

- deep saline aquifers (sedimentary rocks with temperatures between 30 and 150°C, at a depth between 800 m and 3 km),
- hot dry rocks (metamorphic or crystalline with very low primary porosity and permeability, therefore needing fractures to enable geothermal fluid circulation, with temperatures between 90 and 650°C, and at a depth between 2 and 6 km).

We do not consider the following concepts as high potential:

- vapour-dominated and liquid-water-dominated geothermal systems because they tend to occur in extensional, low stress and generally highly permeable geological settings, commonly unsuitable for containment of CO_2, and
- magmatic systems because they do not have the geological conditions required for storage as permeability and porosity (storage coefficient) are likely to be destroyed by the low deformation resistance or rock strength when subjected to high temperatures.

For more information concerning CPG and CO_2-EGS, the reader is referred to the recent review articles of Esteves et al. (2019) and Singh et al. (2020).

3.1.1 *CPG: use of waste supercritical CO_2 as a working fluid in hydrothermal reservoirs*

Description

This concept consists of using CO_2, instead of brine, as a heat vector for geothermal energy mining in “conventional” porous and permeable hydrothermal reservoirs (cf. section 2.5 that explains the benefits of using CO_2 instead of brine), and with simultaneous CO_2 storage. The concept contributes to solving the carbon-reduction challenges in two ways:

- production of energy from renewable, low-carbon sources,
- storage of CO_2 and thus contribution to reduction of carbon emissions.

Often referred to as "CPG" (CO_2 Plume Geothermal) in the literature, this concept was first proposed by Randolph and Saar (2011a, 2011b, 2011c). The system is initialized by CO_2 injection over several months (or a few years) and, once the supercritical CO_2 plume encompasses both the injection and production wells, geothermal exploitation is launched. "Cold" supercritical CO_2 is injected in the injection well and hot CO_2 is pumped (or retrieved if the thermosiphon effect is sufficiently strong) up through the production well. The CO_2 is then used to generate power using a CO_2-compatible turbine or a heat exchanger.

Different numbers are available to illustrate the state of the art and compare efficiencies between CPG and water-driven systems, depending on geological features notably. In most cases, CPG is found to be more efficient, e.g.: for similar exploitation conditions, according to Randolph and Saar (2011b), CPG can provide heat extraction rates of up to three times greater than those of traditional water-based systems; according to Adams et al. (2015), CPG systems produce more electricity than brine-based geothermal systems at depths between 2 and 3 km, and at permeabilities between 10^{-14} and 10^{-13} m^2, often by a factor of two. Above a certain power plant size (around 10 MWe) and some underground characteristics (permeability notably), the advantage of lower viscosity of CO_2 is diminished and supplanted by the higher specific heat of water (Benjamin et al., 2020).

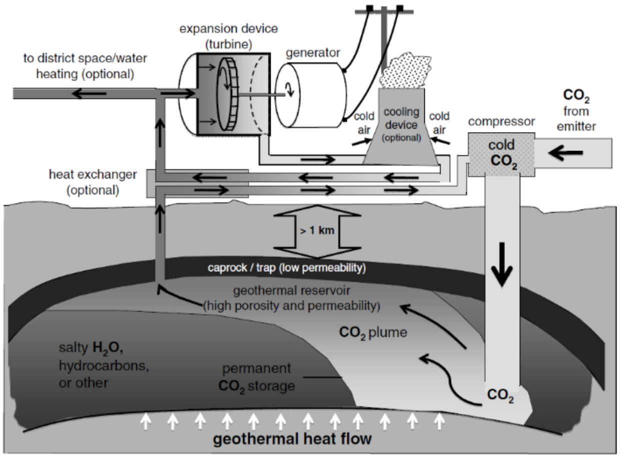


Figure 14. Illustration of the CPG concept (Randolph and Saar, 2011a)

Many authors point towards an extremely wide replicability potential for geothermal power production with CO_2 as a heat vector (e.g. Randolph and Saar, 2011b; Zhang et al., 2014, respectively for USA and China). Due to the lower viscosity of CO_2, the energy extraction rate is feasible even for ranges of permeability that would be too low for brine geothermal exploitation (Figure 15). As a consequence, the potential of deployment for electricity generation is greater for CPG than for brine geothermal electricity production. It is also possible to produce similar power with lower temperature aquifers. For instance, as illustrated in Figure 16, in order to reach electrical generation of 5 MWe at 2.5 km depth, it is necessary to target either a 150°C formation temperature for conventional geothermal extraction or a 98°C formation temperature if the CPG concept is used. CO_2 could also be an alternative to exploit geothermal energy from weakly consolidated sandstone reservoirs due to its high mobility (Cui et al., 2022). The viable formations are thus more widespread for CPG deployment (Figure 16) than for water-driven hydrothermal reservoirs from an energy perspective.

CO_2 storage potential is generally not presented as the primary objective of the technology, but in practice it is not inconsequential. Several tens of Mt of CO_2 can be stored over the life cycle of a single project. The concept is similar to that of CCS (with the addition of one or several production wells), and thus the storage potential of each individual site presents a similar order of magnitude as for a CCS storage site.

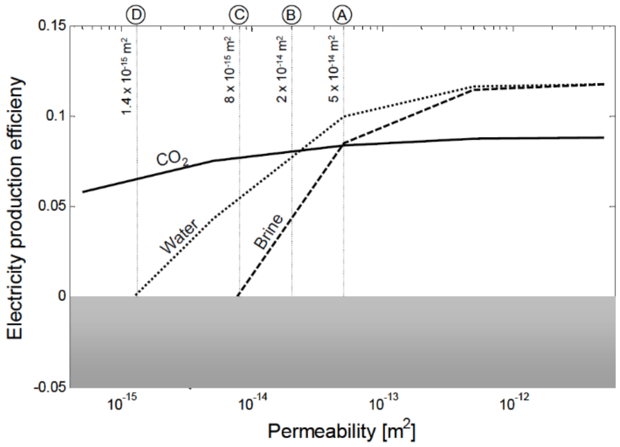


Figure 15. Electricity production efficiency for CPG compared to conventional water geothermal extraction depending on permeability (Randolph and Saar, 2011b). This figure shows how differing kinematic viscosity, heat capacity, and compressibility of supercritical CO_2 combine to provide improved geothermal heat extraction efficiency at low permeability

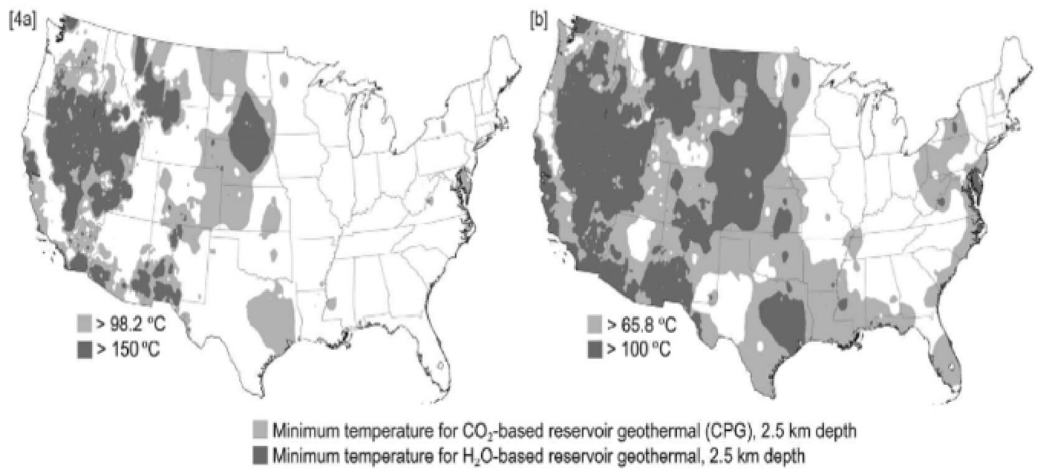


Figure 16. Mapping of viable geothermal regions using CPG (Randolph and Saar, 2011a)

Concerning environmental risks and impacts, in order to contain CO_2 the reservoir must be overlain by a caprock with low permeability. CO_2 leakage risks should be monitored and managed just as rigorously for CPG as for CCS. The risks and potential environmental impacts of the CPG concept have not been considered in detail. Learnings from CCS can however directly be applied. The optimistic high deployment potential from an energy point of view should be tempered by applying the same constraining conditions as required for CCS. The replicability should consider: i) high constraints on overlying formations (caprock) to guarantee the absence of leakage; ii) the availability of a nearby CO_2 source and/or the possibility to deploy a CO_2 transport network from a further industrial CO_2 emitter. The seismic risk is generally moderate for hydrothermal geothermal heat extraction; CPG is likely to limit pressure build up (due to CO_2 production) and the subsequent issues, notably seismic events (Randolph et al., 2013; Adams et al., 2014). Possible geochemical reactions and their consequences (e.g.

loss of injectivity, unwanted pressure increase) should be modelled and monitored, depending on the reservoir's characteristics.

CPG raises some technical challenges. Thermal breakthrough (which occurs when the cooling of the reservoir, due to reinjection of colder water, reaches the production well, with direct consequences on energy performance) should be modelled, predicted and the design of operations should be well-balanced to provide long-term energy production. Some issues are encountered with the layout of wells (Adams, 2015; Adams et al., 2021), the well diameter (Adams, 2015), the management of early brine breakthrough (Hau et al., 2021), and the design of the flow rate to prevent water accumulation (Ezekiel et al., 2022). The effects of H_2S and N_2 impurities on CO_2 migration should be investigated (Yu et al., 2021) as well as other geochemical issues.

Understanding and modelling the underground mechanisms represent scientific challenges. A good review is given in Singh et al. (2020), including current state of the art and perspectives of future works. Numerous models were developed to investigate thermo-hydro-mechanical phenomena (with several codes available such as: TOUGH2/ECO$_2$N, GEOS, FEHM, OpenGeoSys, STOMP, TOUGH+FLAC3D, see Pandey et al., 2018). Geochemical phenomena are often tackled in separate models, even if fully coupled dynamic thermo-hydro-geomechanical models are proposed (Gudala and Govindarajan, 2021).

From an economic perspective, investment costs are high, and the duration of the initialization period (several months/years) with no energy production is a hurdle for investors and will require rethinking of existing business and investment models. Revenue from storage may be useful in advancing the deployment of CO_2 geological storage. According to Adams et al. (2015), who developed a techno-economic simulator (genGEO), using CO_2 as opposed to water as a subsurface heat extraction fluid decreases the cost of geothermal electricity, across most geological conditions that are representative of sedimentary basins. The available techno-economic studies (Miranda and Bielicki, 2021) are limited and should be considered cautiously. Proposed probabilistic estimates for the levelized cost of electricity (LCOE) and showed that these can be lower (thus better) than other energy technologies, but the tail of the distribution commonly extends into LCOEs that are much higher than other energy technologies.

Numerous articles were co-published by the University of Minnesota and ETH-Zurich about CPG (Randolph and Saar, 2011a, 2011c, 2011b; Randolph et al., 2013; Adams et al., 2014; Garapati et al., 2014, 2014; Benjamin M. Adams et al., 2015, 2015; Benjamin M Adams et al., 2015; Garapati et al., 2015, 2015, 2017, 2017; Randolph, 2018; Fleming et al., 2020; Adams et al., 2021; Garapati et al., 2020). Since then, numerous other research teams have worked on the topic. Singh et al. (2020) present an overview of case studies and associated ranges of values. Feasibility studies with promising economic considerations have been proposed for different countries (e.g. Gudala and Govindarajan, 2021, for India, McDonnell et al., 2020, for Germany, Pan et al., 2016, for Mexico). The feasibility of some components of the CPG technology has been accomplished at two existing CO_2 geological storage sites (Aquistore in Canada and SECARB in Mississippi, see Freifeld et al., 2013; Hau et al., 2021; Shokri and Chalaturnyk, 2021) and possibly some others.

Variations of the concept have been proposed in recent years: e.g. Shokri et al. (2022) investigated an intermediate concept with co-injection of CO_2/brine in wells, or alternating CO_2 and brine injection in wells for a case study in Canada.

The concept of CO_2 extraction has been tested in 2015 at the SECARB Cranfield site (Mississippi) at a depth of 3.2 km, but the thermosiphon was not sustainable contrary to model predictions (Pan et al., 2018). No other operational pilot or demonstrator exists. In the absence of pilots, as highlighted by Esteves et al. (2019), “research projects that study the geological storage of CO_2 are also important to understand the behaviour of this geothermal working fluid in the reservoir. This knowledge can be helpful for further studies of the CO_2-based geothermal systems.”

Table 4. An overview of modelling case studies available in the literature (Table 2 from Singh et al., 2020). It should be noted that within this study, some case studies are presented in other sections.

Table 2: Different CPG systems studied. Acronyms of different parameters: T_r and T_i are the reservoir and injection temperature, $\dot{m}$ is the injection rate of CO_2, $\dot{E}$ is the energy production rate and M is the total injected mass.

Authors	H (m)	T_r (°C)	T_i (°C)	$\dot{m}$	$\dot{E}$	M (tonnes)	Injection fluid	Study type
Randolph and Saar (2011a)	2500	100-140	20	300 kg/s	43-68.8 MWt		CO_2	Numerical, TOUGH2+ECO2N
Buscheck et al. (2013)	5000	266	16	480 kg/s	1.9 GWe	15.15×10^6 per year	CO_2	Numerical, NUFT
Elliot et al. (2013)	2500, 5000	104, 133.7, 197.8, 258.7	16, 47, 51	480 kg/s	9-47 MWt/km^2	15×10^6	CO_2	Numerical, ELSA-basin model, NUFT
Kervévan et al. (2014, 2013)	305, 610	60-80	≤ 40			$10^4 - 10^5$ per year for 30 years	95% CO_2 + water	Numerical
Adams et al. (2014, 2015)	1000-5000	35-265		170-417 kg/s	< 18 MWe		CO_2, CO_2 + 20% (water+NaCl)	Semi-analytical, TOUGH2+ECO2N
Garapati et al. (2014)	2500	100				10^7	CO_2	Numerical, TOUGH2+ECO2N
Xu et al. (2014)	3800	150	20				CO_2	Numerical, TOUGHREACT
Garapati et al. (2015)	1500-3500	65-140	35-58			$2-6 \times 10^6$ per year for 2.5 years	CO_2	Numerical, TOUGH2+ECO2N
Zhang et al. (2016b)	3000	85	47.38				$ScCO_2$	Numerical, TOUGHREACT + TOUGH2´CSM
Zhang et al. (2016a)	3500	150	40		0.296-0.537 MWt per year for 40 years		$ScCO_2$	Numerical
Garapati et al. (2017)	2500-4500	100-220	22				CO_2	Semi-analytical, TOUGH2+ECO2N
Pan et al. (2018)	1500-2000	225	35	30 kg/s for 30 years	100 MWt		$ScCO_2$	Numerical, T2Well + TOUGH2+ECO2N
Babaei (2019)	2000	80	20			$1.08 - 3.25 \times 10^6$ per year for 20 years	CO_2	Numerical, ECLIPSE E300

Characteristics

Foreword: Values presented here are indicative: It was chosen to present ranges of values corresponding to those in common use.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs: • a permeable aquifer formation in a sedimentary basin • overlain by an impermeable caprock.	
	Porosity Permeability	[5-20] % [10^{-15}-10^{-13}] m²
Depth	Around 2.5 km. Range [1-4] km	
Dimensions	Thickness Extension	[50-300] m Kilometre scale - Lateral extension [1-2] km

Temperature	[80-200] °C
ENGINEERING	
Wells	Number of wells: • At least one central injection well, • One or several production wells (4 in Randolph and Saar, 2011). Well design requirements: Generally vertical wells, suitable for supercritical CO_2, for temperatures above 100°C Inter-well distance: [500-700] m
Surface installations	Turbine (turbine that works directly with CO_2 or binary-cycle power system). Facilities for injection in supercritical or liquid phase
Geothermal fluid	Supercritical CO_2 Initialization: [100-300] kg/s, several months Operation: [100 - 300] kg/s Reinjection temperature: [30 - 40] °C
INTEGRATION	
Upstream	CO_2 requirements from an external source: • Initialization: [100-300] kg/s, several months • Operation: [5-30] kg/s to compensate loss (estimated loss: 5-10%).
Downstream	Requirements: • Electricity production: connection to a suitable voltage grid • If possible: local valorization of co-produced heat (if Combined Heat and Power production to optimize efficiency)
SERVICES PROVIDED	
Net baseload electricity production	Heat extraction: [10-60] MWth Conversion in electricity: [1-6] MWe
CO_2 geological storage	E.g. initialization phase: 4 Mt CO_2 / Operations: 20 Mt for 30 years. Range: [5-30] Mt CO_2 over 30 years
FROM CONCEPT TO MARKET	
Readiness	First published in 2011. Tens of scientific articles addressing technical design, scientific challenges and modelling. Few articles proposing feasibility studies and economic modelling. A test at Cranfield to demonstrate the thermosiphon effect, with mitigated results.
Proponents and intellectual property	This concept is widely studied and pushed by a group from University of Minnesota and ETHZ (Zürich, Switzerland) (several articles per year since 2011). It has been investigated by numerous other teams worldwide since. A patent in 2012 (Saar et al., 2012)
Availability of economic consideration	Randolph and Saar, 2011b, estimate the power-plant cost at around 3000 $/kW. Considering operational and investment costs presented in Randolph and Saar (2011c), the LCOE can be estimated around 2 $/kWh. Miranda and Bielicki (2021), proposed LCOE distributions mostly ranging between 0.5 and 3 $/kWh.

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

Table 4 provides an overview of case studies modelled in the state of the art. Certain papers listed mention rather high flow rates (up to 480 kg/s). While this is possible in principle, assessing the potential of the method with such rates produces over-optimistic results and perspectives. The variable requirements for the CO_2 flow between initialization and normal operations will be a strong hurdle for practical implementation.

This technique requires a structure that will retain the CO_2 plume and should comply with local CO_2 storage regulations. Reproducing the CO_2 might significantly increase the risk of leakage, with its associated cost of emission credits.

Numerous papers used in this section come from a group of researchers who are keen supporters of CPG or even have commercial interests. This should be kept in mind when reading the very positive conclusion conveyed in most articles.

3.1.2 *Use of supercritical CO_2 as a working fluid in EGS*

Description

Engineered reservoirs have been created “to extract economical amounts of heat from low permeability and/or porosity geothermal resources” (MIT, 2006). These reservoirs are developed in fractured rock formations, initially dry or water-saturated. Water-driven EGS may require the use of water from external resources, which may have detrimental impacts on the economic and environmental performance of the Enhanced Geothermal System (EGS).

The concept referred to as “CO_2-EGS” uses supercritical CO_2 ($scCO_2$) instead of brine as a heat vector in EGS to extract heat from hot rocks (Figure 17). It was first presented by Brown (2000). When using CO_2, one might suppose that fluid loss could be advantageous from an environmental and economic point of view due to the CO_2 stored in the reservoir. The containment of CO_2 in such geological systems should be further demonstrated to support this theoretical advantage.

EGS typically involves deep drilling to a depth of 3-6 km for the production and injection wells, and a EGS geothermal reservoir needs to be stimulated to increase permeability (re-opening of existing fractures or creation of new fractures) using a stimulation fluid. Stimulation techniques generally rely on hydraulic pressure (hydraulic stimulation), thermal difference (thermal stimulation) and/or chemical reactions (chemical stimulation) to open or widen existing fractures or initiate new ones.

Once the system is sufficiently permeable for fluid circulation, CO_2 injection is initiated in the injection well(s), and fluid is produced in the production well(s). Compared to CPG systems, the initialization step is likely to be shorter and require less CO_2. The overall porosity of the reservoir is generally an order of magnitude less than that of a hydrothermal reservoir used simultaneously as a CO_2 storage site. A CO_2-EGS site relies on fracture rather than matrix porosity, which also reduces the ultimate storage capacity of a CO_2-EGS field.

The targeted temperature (150 to 300°C) of deep formations for CO_2-EGS is sufficiently high for the heat extracted to produce electricity: either in a turbine suitable for CO_2 as a working fluid; or through a heat exchanger whose secondary fluid is the working medium for a turbine. The second option is technologically and commercially well established and can deal with the CO_2 reservoir fluids that are highly likely to contain, for example, non-negligible associated water (Figure 18) and other non-condensable gases. Once heat is extracted, the CO_2 is then treated and compressed before reinjection.

Make-up CO_2 is continuously co-injected to compensate any site-dependent fluid losses in the reservoir. Authors estimate the make-up CO_2 to be around 5-10% of the total flow, but there is no field experience. The quantity of CO_2 stored corresponds to the initial CO_2 necessary for system initialization, as well as the continuous CO_2 recharge, which is necessary to maintain reservoir pressure and to compensate for CO_2 loss.

When using CO_2 as a heat-transmission fluid, thermal extraction rates are expected to be approximately 50% larger than when using water (e.g. Pruess, 2006).

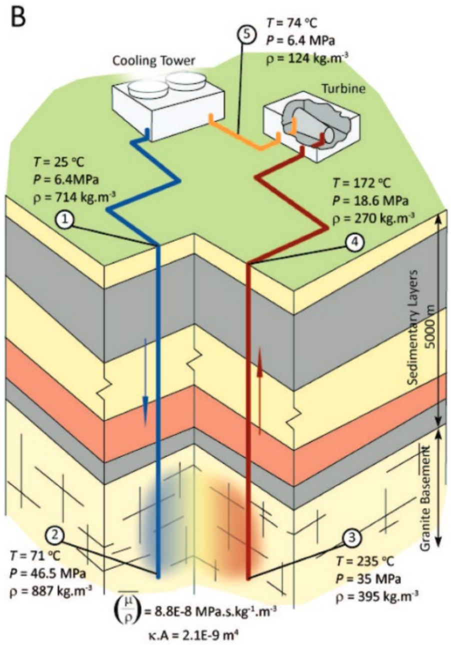


Figure 17. Illustration of the CO_2-EGS concept (Atrens et al., 2009)

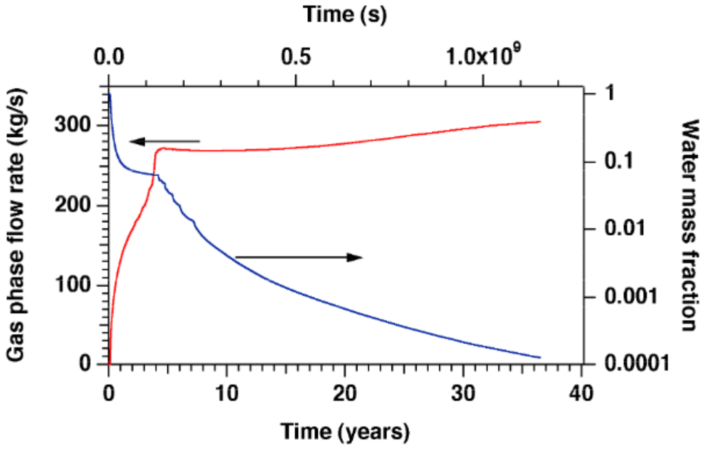


Figure 18. Simulated gas phase flow rate (red) and composition of produced fluid (blue) by (Pruess and Spycher, 2009). The water-phase production ceases after 3.9 years and the water content declines, dropping below 1% after 7.4 years.

Concerning the scale-up and replicability of CO_2-EGS for energy production, no evaluation is proposed in the literature. The TRL is low (in the range 2-3) and the concept and conditions required are not sufficiently demonstrated, which limits the possibility to estimate potential. The replicability will also depend on progress in reservoir engineering and ability to create artificial, i.e. engineered, reservoirs in any type of rock, which remains a challenge. The CO_2 storage objective potential of the concept can vary considerably depending on reservoir typology. Some reservoirs have limited porosity (with an impermeable matrix and circulation limited to a small volume ratio in fractures), thus the storage potential is automatically limited. Zhang et al. (2014) distinguish naturally permeable and potentially porous systems and artificially created reservoirs that do not provide much CO_2 storage capacity. According to Wang et al. (2018), the surrounding formation's permeability has an important influence on the potential for CO_2 storage and heat extraction.

Overall, the potential for CO_2 storage as a co-benefit in CO_2-EGS appears to be lower than for CPG (e.g. Randolph and Saar, 2011c). Esteves et al. (2019) are cautious concerning the storage potential, considering the uncertain fate of CO_2, which prevents conclusions regarding efficient containment without efficient monitoring and containment verification: "the reservoirs are considered an open system, which makes the underground CO_2 injections imprecise and difficult to track and measure. Therefore, the amount of carbonate minerals formed, and the sequestered CO_2 is unclear".

The debate on the storage potential is related to the debate on the ratio of fluid loss. A value of 5-10% is conceptually used, but:

- According to Wang et al. (2018), the question remains open as to whether one can evaluate CO_2 storage based on experimental data of water-based EGS. Considering the different fluid properties, a lower fluid loss ratio is likely, especially at low-to-average reservoir permeability and initial reservoir temperature.
- Concerning the CO_2 driven out of a CO_2-EGS system by possible pressure diffusion, Wu et al. (2021) have estimated the impact of CO_2 being consumed by mineralization to be around 0.05%. When compared with a fluid loss of 5%, mineralization as a trapping mechanism is likely not to be a significant factor for the overall CO_2 fluid loss.
- The results obtained by Xu et al. (2016) suggest that the major CO_2 trapping mechanisms are storage in the fracture-stimulation damaged zone followed by diffusion in the pores within the rock matrix. The assessment suggests that 5% of working fluid loss might be an over-estimate of the long-term CO_2 storage capacity of EGS.

Concerning environmental risks and impacts, the CO2-EGS concept has the same two major issues as water-EGS. Firstly, managing the associated seismicity that comes with increasing permeability and reservoir creation at an EGS site. One may speculate that using CO_2 as a stimulation fluid may have a significant impact on EGS fracture network design owing to the higher mobility of CO_2, which may reduce overpressure and thus make induced seismicity more readily manageable.
Secondly, any "lost" CO_2 may not be automatically considered as "stored" without being able to demonstrate long-term storage through Monitoring, Measurement and Verification protocols, which would need to be established. This is inferred in the review of Singh et al. (2020): "Even though the HDR possesses high heat mining potential, it does not promise CO_2 storage security. Due to the absence of brine in the liquid phase, the injected CO_2 can escape through vertical faults or fractures quickly. The presence of a highly intact low permeability-porosity caprock can only hinder the vertical migration of lighter CO_2."

Technical challenges and optimization of conceptual designs have been the subject of numerous scientific articles. Comparisons of water-based EGS and CO_2-EGS (e.g. Zhang et al., 2013; Wang et al., 2018; Bongole et al., 2019) suggest that CO_2-EGS might be advantageous from several points of view and highlight the complexity of modelling and

understanding. Liu et al. (2022) and Olasolo et al. (2018) extend the optimization of the fluid vector, considering nitrous oxide that may outperform CO_2 on some criteria (notably compressibility, mobility, heat properties). The design of an EGS system is more complex with CO_2 than with water because the behaviour of CO_2 is far more variable with temperature and pressure. Design errors could lead to less heat recovery from the reservoir over the project life span (Pritchett, 2009). For instance, as the reservoir cools, CO_2 mobility increases providing a positive feedback between reservoir cooling and flow, which can lead to rapid thermal breakthrough in the deeper part of the reservoir (Pruess and Spycher, 2009). A solution could be to optimize well perforation, e.g. open the production well only in a limited vertical interval near the top of the reservoir (Pruess, 2008; Luo et al., 2013).
Energy conversion has been the subject of multiple studies. Atrens et al. (2011) proposed optimization of system design in order to maximize economic performance (considering a direct-CO_2 turbine). Other authors investigated optimization of surface installations (separator, turbine, heat exchanger, pre-heater, cooling equipment). Although using CO_2 in a direct CO_2-compatible turbine is sometimes presented as being possible and advantageous considering TRL and impurities (Zhang et al., 2016), using a binary cycle power plant with an appropriate secondary fluid (Mohan et al., 2013, 2015; Bonalumi, 2018) currently appears to be a more reasonable option to circumvent technical issues.
Upscaling of CO_2-EGS and its integration into energy supply hubs has also been the subject of a number of studies. Shi et al. (2018, 2019) proposed the use of horizontal multi-lateral wells that can potentially optimize multilateral-well CO_2-EGS efficiency. Different studies deal with upscaling systems: Mohan et al. (2013, 2015) investigated greater-size systems with 10 injection wells, leading to higher power plant size (40-46 MWe). Mohan et al. (2013, 2015) also discussed the integration with Integrated Gasification Combined Cycle (IGCC). A high pressure gasification process, followed by pre-combustion carbon capture makes the IGCC–EGS pair a symbiotic combination, while other capture process are less appropriate. For a 629 MWe IGCC plant, with capture of 120 kg/s, the energy lost for CO_2 capture is around 50 MWe. Using the CO_2 flux in a CO_2-EGS system with 10 injection wells leads to 46 MWe production, thus recovering most of the energy lost during the storage of CO_2. Jiang et al. (2017) proposed to hybridize the concept with a solar system to increase the system capacity factor by generating additional electric power during peak-demand hours.

Among the technical challenges, the choice of the stimulation fluid is a key consideration. Building on the success of CO_2-stimulation fluids in the oil and gas industry, Brown (2000), suggested using supercritical CO_2 for hydraulic fracturing. Jian et al. (2021) compared the use of four fracturing fluids including water, CO_2, CO_2 with water, and CO_2 with aqueous polyallylamine. Guo et al. (2019), discussed the use of proppants through numerical simulation. Whatever the heat vector for system exploitation, using CO_2 for stimulation may be of interest (Pramudyo et al., 2021) in some conventional and superhot geothermal environments.

Concerning the scientific challenges, notably on understanding underground mechanisms:

- Several challenges exist concerning the correct modelling of thermo-hydro-mechanical phenomena. These are addressed mainly in articles that present case studies. Singh et al. (2020) give an overview of modelling case studies available in the literature.
- Dynamic reservoir simulators have been found to be useful for conceptual studies of CO_2-EGS reservoir systems (Table 6).
- Introducing CO_2 into an EGS reservoir is expected to lead to a range of fluid-rock interactions, some of which will cause reservoir management issues (e.g. production chemistry, inflow and outflow performance). Some of the issues have been investigated from a conceptual and experimental perspective. As reported in Fouillac et al. (2004) and Pruess and Azaroua (2006), reactions between minerals and CO_2 should be relatively rapid at elevated temperatures. CO_2 injection into granitic rock could give rise to the formation of calcite with porosity change (e.g. porosity increase due to dissolution

of wairakite and precipitation of calcite and kaolinite). According to Borgia et al. (2012) and Xu et al. (2015), a likely challenge of CO_2-EGS is salt precipitation. Simulations show that in both low- and high-salinity cases, clogging occurs in very specific areas of the reservoir, namely close to the production and injection wells for low and high salinity, respectively. According to Elidemir and Güleç (2018), another challenge is carbonate precipitation (rather than carbonate dissolution) in fields with high reservoir temperatures, such as Germencik (232°C) and Kızıldere (242°C) in Turkey, whereas in the fields with relatively lower temperatures, dissolution is also an effective process. Xu et al. (2008) studied the peripheral zone where dissolved CO_2 could induce dissolution of primary minerals and precipitation of secondary carbonates. Remoroza et al. (2012) carried out experiments with granite at 200-250°C and observed no significant reactions/ dissolutions of minerals in the presence of supercritical CO_2. Wu et al. (2021) carried out heat extraction experiments involving the alternating cyclic injection of water and supercritical CO_2. However, geothermal field operators have learned to overcome many of the challenges. For example, it is common practice for periodic workovers of injection and production wells as well as chemical stimulation to remediate lower than expected inflow performance (e.g. Barrios et al., 2007; Kamila et al., 2021).

- Geomechanical studies of a fundamental nature suggest no adverse impact when using CO_2 as a working medium to extract heat from a EGS fractured reservoir. For example, Le Zhang et al. (2017) performed experiments on the effect of fracture roughness on heat transfer comparing a rough and a smooth fracture. They showed that heat transfer in the rough fracture was affected by channelling and disturbance effects. Bongole et al. (2019) analysed how the complexity of the fracture geometry influences the fluid flow path and heat transfer efficiency of the thermal reservoir. Chen et al. (2022) investigated fault-compartmentalized, inclined thin reservoirs.

Concerning economic challenges, scoping techno-economic studies emphasize that investment costs are high and development risks put future revenue streams correspondingly at risk. All this poses serious challenges to commercialising conventional water-based EGS, let alone CO_2-EGS. The supply of CO_2 will incur additional investments and, very likely and more importantly, additional operating expenditure. The initial charge and subsequent make-up CO_2 will come at least at a cost of capture to the CO_2 supplier. Conversely, revenues from storage will be useful in advancing the deployment of CO_2-EGS. Atrens et al. (2011) proposed a LCOE of approximately 0.24 $/kWh, but these figures should be considered with caution in view of the diversity of EGS projects and their low TRL.

Numerous research teams have worked on the CO_2-EGS concept worldwide. To our knowledge, there currently exist no feasibility study (it should be noted that Department Of Energy is calling for proposals on demonstration plants in the US), no pilot project and no patent registered against this technology. The only tests found in the literature took place in Japan (Ogachi and Hijiari) where CO_2 was injected in the dissolved form in water in Hot Dry Rocks to study reactivity (Wakahama et al., 2009). According to Xu et al. (2016), "there is still some ways to go for EGS to become an accepted, commercially viable, sustainable energy production technique". This is even more true for CO_2-EGS.

Table 5. Overview of CO_2-EGS modelling case studies available in the literature (Singh et al., 2020)

Table 3: Different HDR geothermal systems studied.

Authors	H (m)	T_r	T_i	$\dot{m}$	$(\dot{E})$	M (tonnes)	Injection fluid	Study type
Brown (2000)	4000	260	40	3 kg/s	10 MWe for 20 years	2×10^6	CO_2	Theoretical
Pruess (2006)	5000	120-240	20		12.83 MWe		CO_2	Numerical, TOUGH2+EOSM
Pruess (2008)	2000	200	20	195-270 kg/s			CO_2	Numerical, TOUGH2+EOSM
Borgia et al. (2013)	3500-4500	160-200	20				CO_2, 45%CO_2+ brine	Numerical, TOUGH2+ECO2H
Luo et al. (2013)	4800-5000	225	27.1	154 kg/s	0.1-0.67 MW-s for 370-1227 days		CO_2	Numerical, FLUENT 6.3
Luo et al. (2014)	4050-4250	137.5-144.1	20	10-150 kg/s for 30 years	1.2-5.3 MW		CO_2	Numerical, Fluent 6.3
Borgia et al. (2017)	2000-3000	200	20			100-500 kg/s for 10 days	CO_2	Numerical, TOUGH2+ECO2N
Zhang et al. (2017)	1000-5000	80, 150, 200					$ScCO_2$	Experiment, Numerical-Fluent 13
Bai et al. (2018)	3800	200					$ScCO_2$	Numerical, COM-SOL+REFPROP9.0
Wang et al. (2019b)	4500-5000	185-200	65				$ScCO_2$	Numerical, in-house code

Table 6. Main realistic CO_2-EGS case studies investigated in the state of the art

	Fenton Hill (US)	Soultz-sous-Forêts (France)	Groß Schonebeck	Acoculco (Mexico)	Habanero (Australia)
References	(Brown, 2000)	(Pruess, 2006; Pruess and Azaroual, 2006; Pruess, 2008; Remoroza et al., 2011; Wang et al., 2019)	(Luo et al., 2013, 2014)	(Pan et al., 2016)	(Xu et al., 2016)
Geology	Impermeable, hot, crystalline rock. Porosity after fracking 1.2x10-3.	Granite, Reservoir thickness 305 m, 2% permeable volume fraction, permeability 50 x 10-15 m² in fractures.	Reservoir treated as porous media. Layered formation with anisotropic permeability between 10-17 and 10-14	Reservoir with fractures (for fractures : permeability 10-14m² and porosity 6%) and impermeable matrix	Reservoir with fractures (granite basement rock).
Engineering	1 injector, 2 producers	5 wells (1 injector, 4 producers), distance inter-well 707 m	2 wells, distance inter-well 424 m	5 wells (1 injector, 4 producers), distance inter-well 500 m	6 wells
Surface installations	Binary-cycle power plant with heat exchange from the hot $ScCO_2$ to a secondary working fluid for use in a Rankine (vapour) cycle	CO_2-compatible turbine after fluid drying to remove water.		Binary-cycle power plant with heat exchange from the hot $ScCO_2$ to a secondary working fluid for use in a Rankine (vapour) cycle	Binary-cycle power plant with heat exchange from the hot $ScCO_2$ to a secondary working fluid for use in a Rankine (vapour) cycle
Code	TOUGH2/EOSM	TOUGH2/EOSM TOUGH2/ECO$_2$N	FLUENT	TOUGH2	TOUGH2
Depth	4 km	5 km	6 km	2 km	4.3 km
Initial temperature	260°C	200°C	225°C	260 °C	250°C
Reinjection temperature	40°C	20°C	27°C	20 °C	
CO_2 injection rate		270-280 kg/s	154 kg/s	105 kg/s	368 kg/s
Fluid loss ratio		5%		5-7%	5%
External CO_2	3 kg/s	14 kg/s		5 kg/s	18 kg/s
Production	10 MWe	75 MWth 12-13 MWe	50 MWth	47 MWth	85MWth 11MWe
CO_2 stored after 30 years	2.8 Mt	13 Mt		3.6 Mt	17 Mt
Initialization		1-2 months			

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept targets non permeable formations (e.g. HDR) with permeable fractures (after stimulation). The fluid circulation occurs generally mainly in fractures, but double-porosity systems (fractures and matrix) are also presented. Different assumptions are made for permeability modelling in fractures.	
	Porosity Permeability	Generally low (a few percent) $[10^{-16}-10^{-12}]$ m². Highly variable depending on case studies and assumptions.
Depth	Around [3 - 6] km	
Dimensions	Thickness Extension	[50-300] m Kilometre scale - Lateral extension [1-2] km
Temperature	[160-300] °C	

ENGINEERING	
Wells	Number of wells: • At least one central injection well, • One or several production wells. Well design requirements: Generally vertical wells, suitable for supercritical CO_2, for temperature above 150°C Inter-well distance: Several hundreds of metres, e.g. 500 m
Surface installations	Turbine (turbine that works directly with CO_2 or binary-cycle power system) Facilities for injection of make-up CO_2 in supercritical or liquid phase
Geothermal fluid	Supercritical CO_2 Operation: [100-300] kg/s (initialization poorly addressed, it seems that production might start with brine when using an ORC turbine) Reinjection temperature: [30-40] °C
INTEGRATION	
Upstream	CO_2 requirements from external source: [5-15] kg/s to compensate loss (estimated loss: 5%).
Downstream	Requirements: • Electricity production: connection to suitable voltage grid • If possible: local valorization of co-produced heat (if Combined Heat and Power production to optimize efficiency)
SERVICES PROVIDED	
Net baseload electricity production	Heat extraction: [30-90] MWth Conversion in electricity: [5-15] MWe
CO_2 geological storage	Range (uncertain): [2-15] Mt CO_2 over 30 years
FROM CONCEPT TO MARKET	
Readiness	Concept first published in 2000 Scientific articles with technical (underground and system modelling) and economic modelling. 5 case studies using water-EGS systems as reference. No pilot or demonstrator (to our knowledge).
Proponents	Mostly academic and research laboratories community.
Availability of economic consideration	Limited information: Atrens et al. (2011) mentioned 0.24$/kWh.

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

Table 6 provides an overview of case studies modelled in the state of the art. The figures are rather optimistic or even unrealistic, and may lead to overoptimistic performance indicators. This technique requires a structure that will retain the CO_2 plume and should comply with local CO_2 storage regulations. The available arguments are currently insufficient to consider "fluid loss" as permanent CO_2 storage.

3.1.3 *Heat mining with supercritical CO_2 in depleted oil/gas reservoirs*

Description

CO_2 has been widely used to assist/enhance hydrocarbon 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 facilitates (oil/gas) production at the end of the exploitation period when the reservoir is partly depleted. CO_2 also changes the viscosity of the remaining oil, thus facilitating flow. These techniques are out of the scope of the present study, since there is no hybridization with geothermal energy extraction.

Novel techniques have been proposed recently to progress the concept and to use existing facilities in depleted hydrocarbon reservoirs to (co-)produce geothermal energy with supercritical CO_2 as a heat vector. Different variants are proposed, but the general idea is illustrated in Figure 19 for a gas reservoir. After primary recovery of the gas, CO_2 is injected to enhance the final stages of production. Once the reservoir is no longer economically exploitable for gas/oil alone, it can be transformed for (co-)production of gas and/or geothermal heat with CO_2 as a heat vector.
Natural gas reservoirs are particularly suited for CO_2 storage due to the self-proven sealing conditions of natural gas. As an additional advantage, the available knowledge of geological conditions and existing wells in the field facilitate implementation at lower cost than most other concepts.

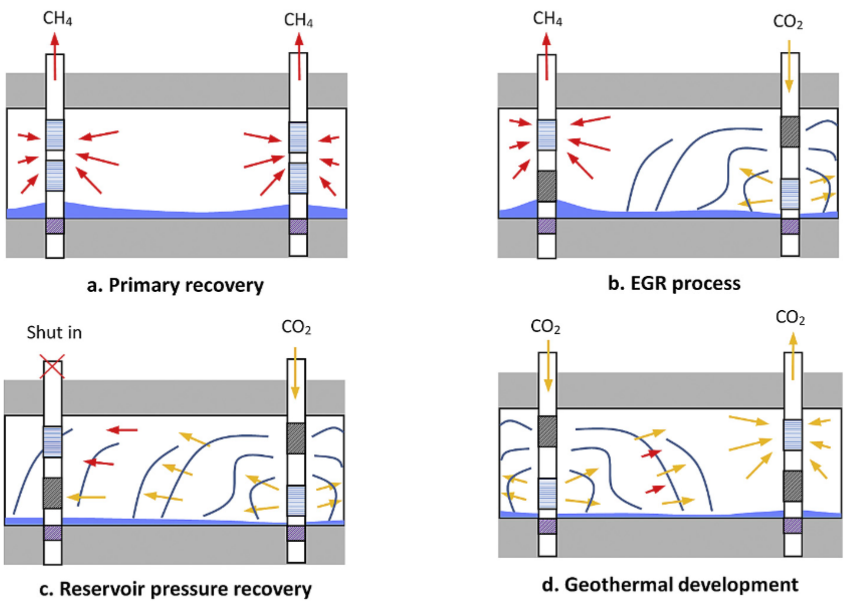


Figure 19. Sequential exploitation of a gas reservoir. a. Primary recovery, all the well sections are open for gas production; b. EGR process; c. Pressure recovery; d. geothermal production with CO_2 (Liang Zhang et al., 2017)

Different sequential exploitations might be possible. For instance, massive CO_2 injection might precede or follow geothermal heat extraction (see Figure 20). During the heat mining phase, gas production is no longer self-profitable; however, the produced additional natural gas can be used to compensate the cost of CO_2 injection. Figure 21 illustrates the possible layout of such hybridization.

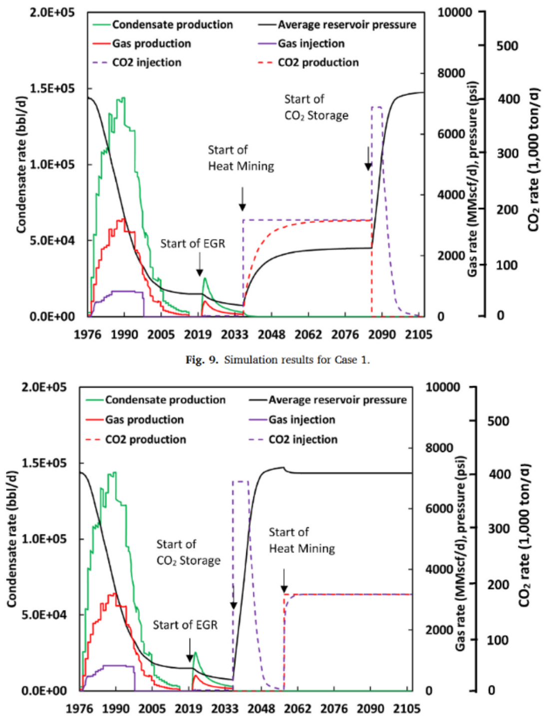


Figure 20. Illustration of different possible sequential exploitations. Top: Heat mining precedes massive CO_2 storage. Bottom: pressure is first recovered with CO_2 injection (without production), and heat mining starts once the initial reservoir pressure is reached (Zhang and Lau, 2022)

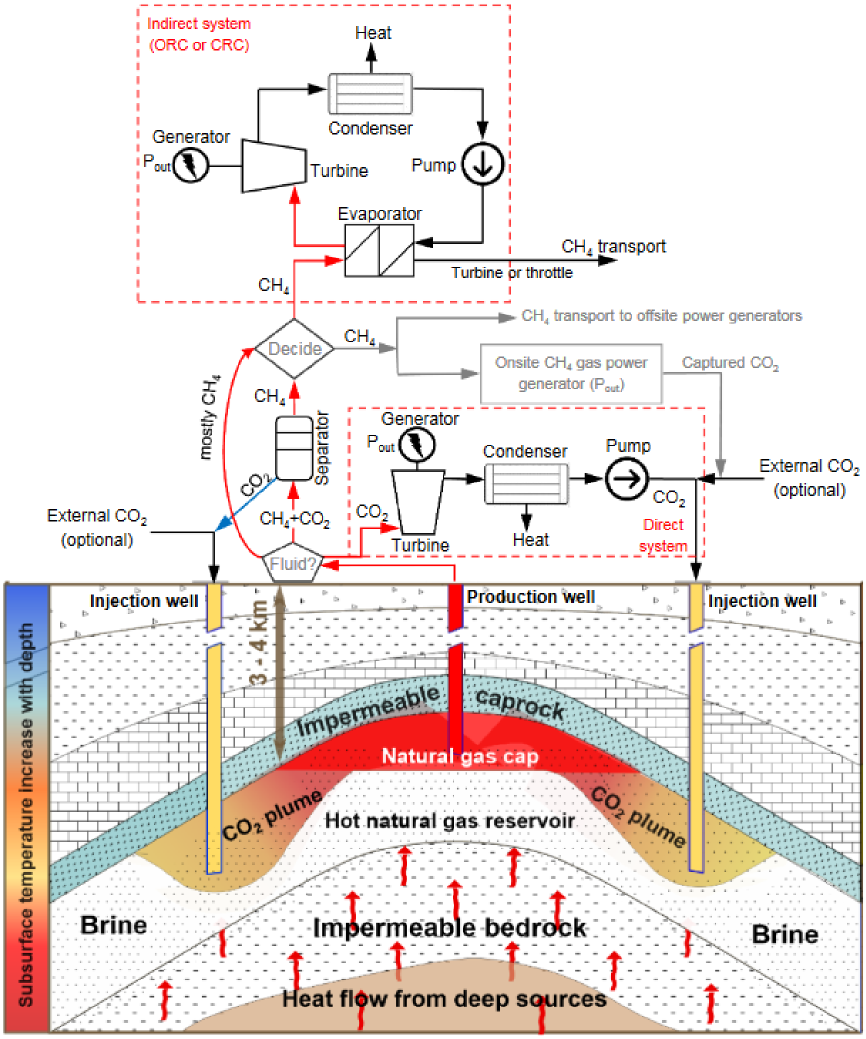


Figure 21. Illustration of reservoir and surface components for CO_2 injection into a deep, hot natural gas reservoir for co-production of natural gas, CO_2 and heat, i.e. a combined CO_2-EGR–CPG system (Ezekiel et al., 2020)

Examples of hybridization of EOR/EGR with CO_2 storage and geothermal heat extraction are presented in Table 7.
The main technical challenges mentioned by authors are the effects of residual methane, of H_2S and of water saturation, as well as the importance of the sequential design and possible salt precipitation and corrosion issues.

Table 7. Main hybridization CCS-geothermal energy extraction in depleted oil/gas reservoirs

References	**(Liang Zhang et al., 2017)**	**(Zhang and Lau, 2022)**	(Ezekiel et al., 2020, 2022)	(Cui et al., 2016, 2022)	**(Chen et al., 2021)**	**(Guo et al., 2019)**	(Shogenov and Shogenova, 2019)
EOR/EGR	EGR	EGR	EGR	EGR	Depleted petroleum reservoir	Abandoned oilfield	EOR
Country	China	Arun, Indonesia	/	/	North Oman	China	Estonia
Geology	Sandstone, carbonate or volcanic rocks Porosity 15%, permeability 10^{-14}m²	Carbonate reservoir - Permeability 10^{-15}-10^{-13}m²	Sandstone reservoir Permeability 10^{-13}m², porosity 20%	Permeability 10^{-15}-10^{-13}m²	Thin-layered and fault-compartmentalized reservoirs Permeability 10^{-15}-10^{-13}m²	Dolomite Porosity 6%, Permeability 10^{-13}m²	Limestone oil reservoir Porosity 10-24% Permeability 10^{-15}-10^{-14}m²
Steps	1. Primary recovery 2. EGR with CO_2 3. Pressure recovery 4. Heat mining	1. Primary recovery 2. EGR with CO_2 3. Heat mining 4. CO_2 storage (pressure recovery)	1. Primary recovery 2. EGR with CO_2 3. (Plume establishment with pressure increase) 3. Heat mining 4. (CO_2 storage - pressure recovery)	1. Primary oil recovery 2. Heat mining	1. Primary oil recovery 2. CO_2 Plume establishment 3. Heat mining	1. Primary oil recovery 2. Heat mining	1. CO_2 injection in a deeper formation and primary oil recovery in a shallower formation 2. Heat mining with/without leakage between formations (2 scenarios)
Engineering		30 injectors, 47 producers	4 injectors, 4 producers	1 injector, 1 producer	1 horizontal injector, 1 horizontal producer	1 injector, 2-4 producers	At least 2 injectors and 2 producers
Depth m	3000	3000	3000	3500	2250	1000-3000	800-1700
Initial temperature °C	150	178	120-150	130-150	100-120	50-105	36-88
CO_2 flux	?	2000 kg/s	110-120 kg/s	18-34 kg/s	20kg/s (15kg/s from production)	100 kg/s	
Production	2-4 MWth	~200 MWe (7 years)	~1-2 MWe	~4-5MWth	7 MWth	~10 MWth	
CO_2 stored at closure	2-3 Mt	1200 Mt	~16		~6 Mt	?	> 2Mt

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to use extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept targets are gas or oil reservoirs, once production is no longer profitable. Particularly suited to reservoirs that have been exploited with EOR or EGR, with an established CO_2 plume. Porous/permeable formations, possibly with fractures	
	Porosity Permeability	6-20% [10^{-15}-10^{-13}] m².
Depth	Around [2-4] km	
Dimensions	Thickness Extension	[50-300] m Kilometre scale
Temperature	[100-150] °C	
ENGINEERING		

Wells	Number of wells: At least one injector and one producer. Already-existing infrastructure might be reused. A significant number of wells could be reused in certain cases with limited investment. Horizontal wells improve injectivity/productivity. Unused wells would need to be completely sealed to prevent leakage.
Surface installations	Fluid pre-processing facilities if the fluid is not sufficiently pure and for gas separation. Turbine (turbine that works directly with CO_2 or binary-cycle power system) for heat mining Gas turbine to exploit residual gas content. Facilities for CO_2 injection in supercritical state
Geothermal fluid	Supercritical CO_2 Operation: [20-100] kg/s for medium-size operation, up to 2,000 kg/s for large-scale field operations
INTEGRATION	
Upstream	Limited information concerning CO_2 requirements from an external source: during the pressure recovery, no CO_2 is produced, and [20-100] kg/s is probably a good order of magnitude for medium-size operations. During heat mining, a lower external flux is expected, since most CO_2 comes from producers.
Downstream	Requirements: • Electricity production: connection to suitable voltage grid • If possible: local valorization of co-produced heat
SERVICES PROVIDED	
Net baseload electricity production	Heat extraction: [2-10] MWth; Conversion in electricity: [1-3] MWe for medium-size deployment. With large-scale deployment, values up to 200 MWe might be possible.
CO_2 geological storage	Range (uncertain): [2-16] Mt CO_2 over variable periods of time, including pressure recovery step for medium-size deployment. With large-scale deployment, values up to 1,200 Mt could be possible.
FROM CONCEPT TO MARKET	
Readiness	Published in recent years, even if CO_2-EOR and CO_2-EGR have been deployed for a long time. Around ten scientific papers. The concept of CO_2 extraction has been tested in 2015 at the SECARB Cranfield site (Mississippi) at a depth of 3.2 km, but the thermosiphon was not sustainable contrary to model predictions (Pan et al., 2018). No other feasibility study or demonstrator (to our knowledge)
Proponents	Investigated by numerous teams worldwide.
Availability of economic consideration	Limited information. See for instance Zhang and Lau (2022).

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

Table 7 provides an overview of case studies modelled in the state of the art. Some of the papers listed mention high flow rates, even values considered as unrealistic. While possible in principle, assessing the potential of the method with such rates produces overoptimistic results and perspectives.

This technique requires a structure that will retain the CO_2 plume and should comply with local CO_2 storage regulations. A potential concern for hybridization in natural gas reservoirs would be the integrity of shut-in legacy wells, which could serve as pathways for CO_2 leakage out of the natural gas reservoir. Unused wells would need to be completely sealed to prevent leakage. In general, the use of a site with multiple wells will increase the leakage potential. Monitoring wells may be needed in the region above the confining caprock to be sure that CO_2 does not leak from the reservoir.

Residual methane and oil will contaminate any produced CO_2, causing fouling issues as well as possible corrosion of surface equipment.

3.1.4 *Energy storage with CO_2*

Another variant is a combination of geothermal energy utilization coupled with underground energy storage. Referred to as UTES (Underground Thermal Energy Storage), the motivations are notably: i) the integration of intermittent renewable energy sources and the associated matching requirements between energy production and energy consumption, dealing with diurnal or seasonal fluctuations; and ii) the valorization of excess heat produced but not valorized (e.g. industrial waste energy of heat produced by a waste incineration plant). The concept focuses on using surface excess energy to heat or compress a working fluid which is then stored underground. For example, an energized fluid can be injected underground in aquifers (ATES), in mines (MTES) or circulated in boreholes (BTES) with heat transferred to the groundwater or rock. When energy demand exceeds energy production, energy is retrieved from the storage.

Recent work investigated the use of CO_2 as a working fluid for thermal energy storage technologies (see references below).

3.1.4.1 CPG-Energy Storage or CPG-Flexible

Description

This energy storage solution relies on the concept of CPG and thus provides the following functionalities:

- Possible dispatchable power production for baseload electricity production;
- CO_2 storage.

In addition, it can be used to provide an electricity storage service in order to balance supply and demand (e.g. to smooth the intermittent production of other renewable energy such as wind or solar), on a daily basis (four duty cycles were selected for production periods of 16h, 12h, 8h and 4h). It is called CPG-F (for Flexible in Fleming et al., 2022) or CPG-ES (for Energy Storage in Adams et al., 2019).

The concept offers full-flexibility between the two energy services, from 100% continuous electricity production to 100% storage service. It can be used simultaneously to produce baseload electricity and store electricity.

When exploiting geothermal energy in deep aquifers with supercritical CO_2 as a working fluid, the energy consumption comes from adapting CO_2 temperature and pressure for reinjection at depth. The gross power production is thus reduced by the parasitic energy required, and the resulting net energy production is lower. Adams et al. (2019) and Fleming et al. (2018, 2022) proposed to time-shift the load required for CO_2 deep reinjection. When electricity demand is higher than supply, CO_2 is exploited in the high-pressure turbine but is not reinjected at depth. Minimal parasitic load is used to inject CO_2 temporarily in a shallow aquifer. The net power production is thus significantly increased. Conversely, once the balance between electricity demand and supply reverses, electricity is retrieved from the grid to inject CO_2 in the deep aquifer. Compared to a simple CPG system, the maximal power production is increased, but the cumulated energy production is decreased (due to energy required for temporary storage in the shallow aquifer).

The concept is illustrated in Figure 22. After electricity production in the high-pressure turbine, the following options exist:

- inject the expanded CO_2 in the shallow reservoir for temporary storage;
- expand the CO_2 through another low-pressure turbine to produce more power before cooling and reinjecting it into the deeper reservoir like in a standard CPG power plant.

The flow can be divided with a chosen portion for baseload power production and the remaining flux for energy storage.

The underground circulation of CO_2 includes the following:

- It is injected at the bottom of the deep reservoir, in the centre. Due to buoyancy, it migrates towards the caprock and extracts heat from the entire thickness.
- It is then pumped from the top of the deep aquifer, with a mass fraction over 94% (required for CO_2 turbines). The extraction wells form a ring around the injection well (vertical wells with a horizontal component in order to optimize CO_2 extraction).
- For possible intermediate storage in the shallower aquifer, reversible wells are used. There is no heat extraction objective in the shallow aquifer; it is only designed for temporary storage (the CO_2 is stored isothermally).

It should be noted that this concept requires an initialization period, estimated to be around 2.5 years to develop the CO_2 plume in the deeper reservoir as well as in the shallow reservoir (shorter duration).

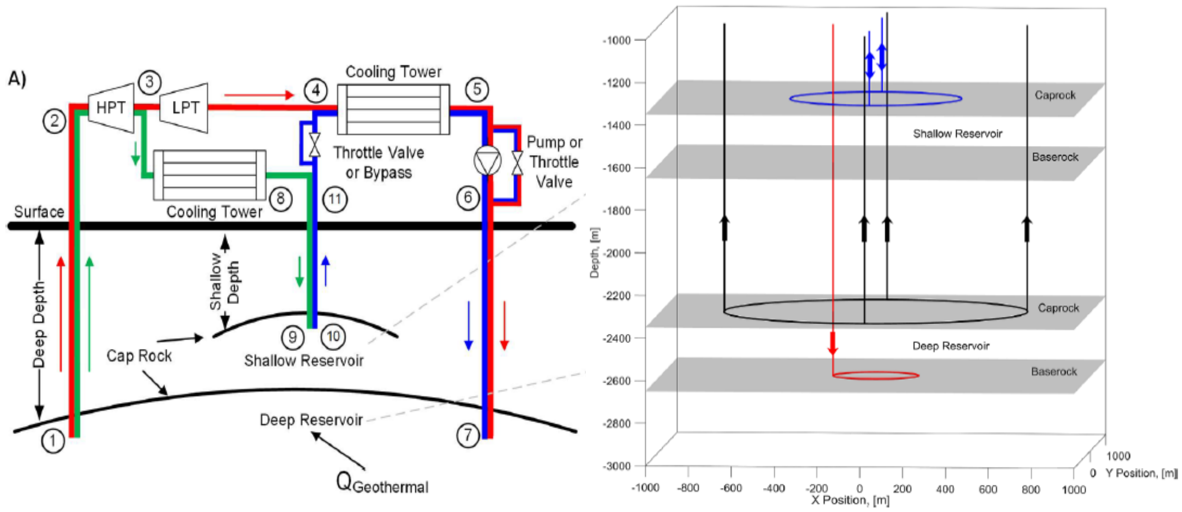


Figure 22. Illustration of the CPG-F concept (Fleming et al., 2022)

Regarding technical and scientific challenges, environmental impacts, etc., most points raised in section 3.1.1 are also valid for CPG-F (since the technique relies on CPG).

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

<table>
<tr><th colspan="3">UNDERGROUND CHARACTERISTICS</th></tr>
<tr><td rowspan="2">Geology and petrophysical properties</td><td colspan="2">The concept needs:
a permeable aquifer formation in a sedimentary basin, overlain by an impermeable caprock.
A secondary shallower aquifer overlain by an impermeable caprock in the vicinity.</td></tr>
<tr><td>Porosity
Permeability</td><td>[5-20] %
[10^{-15}-10^{-13}] m²</td></tr>
<tr><td>Depth</td><td colspan="2">Deeper aquifer: Around 2.5 km.
Shallower aquifer: between 1 and 2 km to maintain CO_2 in supercritical state</td></tr>
<tr><td>Dimensions</td><td>Thickness
Extension</td><td>~300 m
Kilometre scale - Lateral extension [1-3] km</td></tr>
<tr><td>Temperature</td><td colspan="2">Deeper aquifer: Around 100°C
Shallower aquifer: Proposed value in simulations 67°C</td></tr>
<tr><th colspan="3">ENGINEERING</th></tr>
<tr><td>Wells</td><td colspan="2">Three well rings:
Reversible well in the shallower aquifer (2 wells)
Injection well at the bottom of the deep aquifer (1 well)
Production well at the top of the deep aquifer (4 wells).
Once at the reservoir, the vertical wells connect to the horizontal collection wells. These would likely not be circular but rather linear or bent as the CO_2 plume is likely to be diverted in a preferred direction.
Well design requirements: rather horizontal wells, suitable for supercritical CO_2, for temperature around 100°C
Inter-well distance: ~500 m</td></tr>
<tr><td>Surface installations</td><td colspan="2">Turbine (turbine that works directly with CO_2 or binary-cycle power system)
Facilities for injection in supercritical phase, for both aquifers.</td></tr>
<tr><td>Geothermal fluid</td><td colspan="2">Supercritical CO_2
Initialization:
Deep aquifer: CO_2 is continuously injected for 2.5 years (200 kg/s) with no production (15.8 Mt)
Shallow reservoir: CO_2 is continuously injected for 12 weeks (ramp to 100 kg/s) with no production (0.67 Mt)
Operation: [100-600] kg/s</td></tr>
<tr><th colspan="3">INTEGRATION</th></tr>
<tr><td>Upstream</td><td colspan="2">CO_2 requirements from external source:
Initialization: up to 300kg/s
Operation: [5-30] kg/s to compensate loss (estimated loss: 5%).</td></tr>
<tr><td>Downstream</td><td colspan="2">Requirements:
Electricity storage and production: connection to suitable voltage grid
If possible: local valorization of co-produced heat (if Combined Heat and Power production to optimize efficiency)</td></tr>
<tr><th colspan="3">SERVICES PROVIDED</th></tr>
</table>

Net baseload electricity production	Conversion in electricity: [1- 2.5] MWe
Electricity storage	Daily energy storage: • During the discharge period, the net power can reach 10 MWe for short duty cycles (4h production per day). • During the charging period, the net negative power (retrieved from the grid) might be comprised between 0 MWe and ~-15 MWe, for cycles with short charging periods (8h). Possibility of seasonal energy storage also mentioned in Fleming et al., 2018, with 3 months of storage (possibility to store 2-4 GWh over the entire cycle) and 3 months of power generation.
CO_2 geological storage	E.g. initialization phase: ~15 Mt CO_2 / Operations: 5-30 Mt for 30 years. Range: [20-45] Mt CO_2 over 30 years
FROM CONCEPT TO MARKET	
Readiness	First published in 2016. Three scientific articles with technical (underground modelling with TOUGH2/ECO$_2$N) and economic modelling. No realistic case study or demonstrator (to our knowledge).
Proponents	This technology is proposed by a group from University of Minnesota and ETH-Zurich (Zürich, Switzerland).
Availability of economic consideration	Power-plant cost is comprised between 15,000 and 95,000 US dollars per net kW (extrapolated from figures provided in Fleming et al., 2022, section 3.4), considering maximal net power production. Between +34% and +65% compared to simple CPG. LCOE: information not provided

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

The variable requirements for the CO_2 flow between initialization and normal operations will be a strong hurdle for practical implementation.

The purity of 94% of CO_2 for the geothermal fluid production will depend on numerous parameters and might be difficult to obtain and maintain over the life span of operations.

One of the main differences between CPG-ES and CPG is that the overall volume of CO_2 is not kept constant through the cycles in the reservoir. Pore space in some parts of the reservoir are thus constantly alternating between reservoir fluids and CO_2. This results in notable geochemical alteration as the rocks are watered and desiccated by the CO_2. This may lead to significant mineral alteration and degradation of the formation, thus increasing the risk of geomechanical changes in the reservoir.

This technique requires two closed structures at different depths that will retain the CO_2 plume and should comply with local CO_2 storage regulations. Reproducing the CO_2 might increase the risk of leakage, with its associated cost of emission credits.

This class of concepts appears particularly complex and thus hardly practicable, even if theoretically attractive. CPG-alone is already challenging from a practical viewpoint. The addition of an intermediary shallower storage makes the TRL of such a concept very low.

Most of the papers used in this section come from a group of researchers who are keen supporters of CPG and its declinations, or even have commercial interests. This should be kept in mind when reading the very positive conclusion conveyed in most articles.

3.1.4.2 Multi-fluid geothermal energy system (with possible CO2-Bulk Energy Storage and Thermal Energy Storage uses), also called "Earth Battery"

Description

Bulk Energy Storage (BES) refers to energy storage that has a large energy capacity and charges or discharges over periods of a few hours. These high-energy, slow-discharge technologies include pumped hydro, compressed air energy storage, and some types of chemical energy storage (Hittinger and Azevedo, 2015).

Buscheck et al. (2014, 2016) and Ogland-Hand et al. (2019, 2021) proposed a concept, in a permeable reservoir formation at a depth between 3 and 5 km, that combines:

- Geothermal energy exploitation (using brine and CO_2 as fluid vectors)
- CO_2 storage
- BES with a CO_2-pressurized cushion gas.

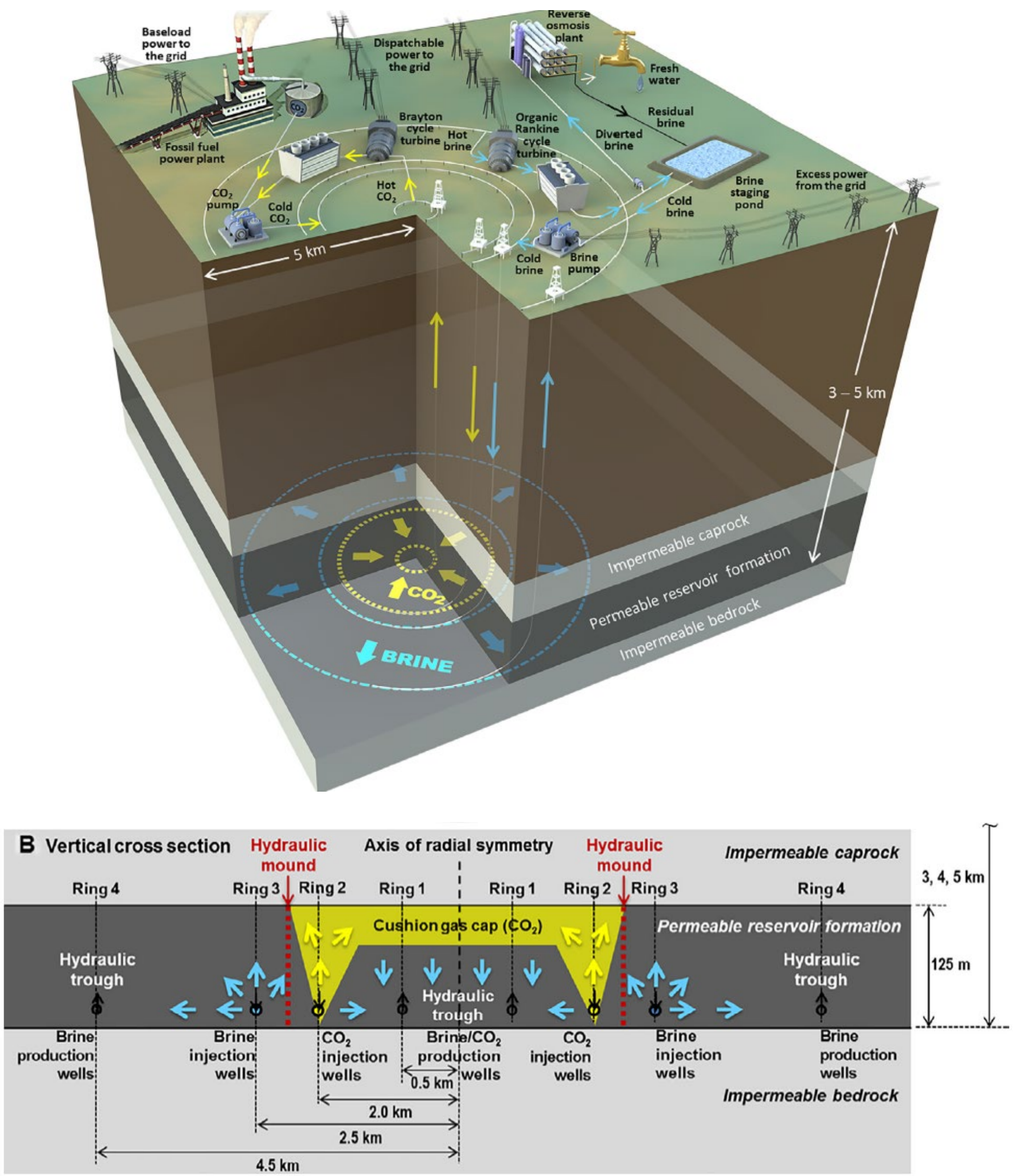


Figure 23. Illustrations of the concept of CO_2-BES (Buscheck et al., 2016a)

The concept relies on a much engineered reservoir management with different concentric rings. CO_2 from an external source (e.g. fossil-fuel power plant) is injected at the bottom of the second ring (25°C). 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). The fluid produced through ring 1 may consist of supercritical CO_2 (in this case a Brayton cycle turbine is used to convert the energy to electricity) and/or hot brine (in this case an Organic Rankine Cycle turbine is used). The concept illustrated in Figure 23 (top) conveys the impression that CO_2-only is produced in the first ring. However, according to the vertical cross section, the production wells are rather located in the brine zone. The description provided in Buscheck et al. (2014) also favours brine production in the first ring. The hot brine,

once exploited for electricity generation, is reinjected in the reservoir in the third ring (65°C), thus contributing to the hydraulic mound that contains the CO_2 plume (called "hydraulic divide"). Together with the impermeable caprock and bedrock, the hydraulic mound forms a container to store pressure, in the form of compressed CO_2 and/or N_2. The injected cold brine warms up when migrating to the outside of the system, where it is exploited for supplementary energy extraction on the fourth ring.
The system can be used continuously for base load energy production (continuous dispatchable power), but the main intention is to use it for daily energy storage.
Brine is stored at the surface in tanks during unload (strong energy needs), and the only parasitic load is for CO_2 reinjection. During system loading periods, brine is pressurized and injected. The possibility to time-shift these parasitic loads provides an energy storage service.

Variations

In addition to CO_2, the cushion gas may be composed of N_2 to increase and store pressure with efficient working fluids and additional flexibility (availability of N_2 is simpler than CO_2).
Another option, instead of injecting cold brine in the third ring, consists of injecting warm brine in order to simultaneously perform Thermal Energy Storage (TES), for instance from Concentrated Solar Power or baseload power plant (e.g. waste energy from nuclear power plant), storing pressurized water in the 300°C range during the night.

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs a permeable reservoir formation in sedimentary basins overlain by an impermeable caprock. Ideally, the permeable formation should be underlain by an impermeable bedrock for proper pressure containment.	
	Porosity Permeability	e.g. 12% e.g. 10^{-13} m²
Depth	[3-5] km	
Dimensions	Thickness Extension	e.g. 125 m Diameter around 10 km for the whole system. Diameter around 4 km for the CO_2 plume.
Temperature	[130-200] °C	
ENGINEERING		
Wells	4 well rings (either arc-shaped wells or high number of wells, order of magnitude: 42-75 wells in Buscheck et al., 2016) The distance between injection and production rings is ~1500-2500 m.	
Surface installations	ORC turbine for electricity production with hot brine Brayton cycle turbine for electricity production with supercritical CO_2 Brine staging pond for bulk energy storage Facilities for injection in supercritical phase.	
Geothermal fluid	The recycled CO_2 flow rate is in the range of 2000 kg/s (Ogland-Hand et al., 2021) and the external inflow around 15-240 kg/s. This flow is injected through a dozen wells with injection rates around 120 kg/s at temperature ~25°C. The maximal brine production/injection rates are comprised between 3,000 and 6,000 kg/s for all wells. The reinjection temperature is ~65°C.	

INTEGRATION	
Upstream	CO_2 requirements from external source: between 15 and 240 kg/s
Downstream	Requirements: • Electricity storage and production: connection to suitable voltage grid • If possible: local valorization of co-produced heat (if Combined Heat and Power production to optimize efficiency)
SERVICES PROVIDED	
Net baseload electricity production	The system can be operated continuously with no BES service and in this case the order of magnitude for electricity production will be comprised between 50 and 300 MWe depending on depth.
Energy storage	In order to match electricity production and demand (and thus contribute to a higher penetration rate of variable renewable energy technologies), the CO_2-BES concept can store excess power from the grid when there is low-demand. The demanding parasitic load corresponds to brine reinjection. During the recharge period, the brine stored in the surface pond is injected in the reservoir. The net negative power (retrieved from the grid) might be comprised between 0 MWe and 250 MWe, during 6 hours (for instance night slot or windy slot) for daily cycles. During the discharge period, the brine injection is interrupted and the net power supplied to the grid can reach 100-500 MWe (twice compared to baseload production).
CO_2 **geological storage**	Range: [50-160] Mt CO_2 over 30 years
FROM CONCEPT TO MARKET	
Readiness	First published in 2014. Modelling work presented in afore-mentioned articles (code NUFT) include underground numerical modelling, as well as surface installations modelling. The integration of the technology in wider energy systems has been investigated by Ogland-Hand et al. (2019). To our knowledge, no pilot or demonstrator has been developed. A case study is proposed in the US state of Wyoming in Ogland-Hand et al. (2021).
Proponents	This technology is proposed by a group of proponents from Lawrence Livermore National Laboratory, University of Minnesota and ETH-Zurich (Zürich).
Availability of economic consideration	According to Buscheck et al. (2016), power-plant cost ranges between 1700 and 3250 US dollars per net kWe. The LCOE is in the range 8-16 US-cents$/kWh for greenfield operations (new site) and in the range 3-6 US-cents$/kWh for brownfield operations (former site already explored and/or exploited). These costs should be considered cautiously; they are probably over-optimistic and do not consider the whole chain (integrating capture costs).

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

The variable requirements for the CO_2 flow between initialization and normal operations will be a strong hurdle for practical implementation.

During the brine storage at the surface, the temperature of the brine will significantly decrease, which may lead to serious scaling issues. The geochemical aspects of CO_2-BES in terms of the fluid handling are very similar to conventional geothermal, and therefore should be considered. Acid dosing and consideration of the final reinjection temperature should be taken into account. This may have notable implications on the process effectiveness and feasibility. Authors of the concept did not introduce such considerations in their conceptual model.

This technique requires a structure that will retain the CO_2 plume and should comply with local CO_2 storage regulations. Reproducing the CO_2 might significantly increase the risk of leakage, with its associated cost of emission credits. This technique requires a large number of wells, which represent additional risk of CO_2 leakage.

This class of concepts appears particularly complex and thus hardly practicable, even if theoretically attractive. The TRL of such a concept is very low.

Most of the papers used in this section come from a group of researchers who are keen supporters of CPG and its declinations, some even have commercial interests. This should be kept in mind when reading the very positive conclusion conveyed in most articles.

3.2 Water-driven geothermal heat extraction with CO_2 (re)injection

3.2.1 *Overview of pilots, demonstrators and projects*

As a foreword, before presenting the technical concepts, we introduce the landscape of projects, pilots and demonstrators. A variety of closely related and physically co-located concepts exists, sometimes grouped under a similar umbrella within multi-partner multi-site projects. For clarity, the projects are introduced first, followed by an explanation of the categorization proposed in the subsequent sections.

Contrary to concepts presented in section 3.1, most technological concepts presented in this section are demonstration projects at progressively increasing scale, rather than theoretical case studies.

In this section, we present the pilots and demonstrators and corresponding figures. In the subsequent sections, we present information corresponding to industrial scale deployment for the sake of comparison.

CARBFIX, GECO, SUCCEED

The major group of projects stems from the initial CarbFix project. Under this CarbFix umbrella, several projects should be considered:

- Project CarbFix1 (2012-2014), with demonstrators at Hellisheidi (Iceland) (shallow reservoir). The objective was to demonstrate CO_2 storage by rapid mineralization in a basaltic environment.
- Project CarbFix2, with demonstrators at Hellisheidi (Iceland) (deep reservoir).
- Project GECO (Geothermal Emission Control, H2020, 2019-2023), with demonstrators at Hellisheidi and Nesjavellir (Iceland), Kızıldere (Turkey), Hveragerði (Iceland) (substituting Castelnuovo in Italy), and Bochum Mule in Germany. It aims to provide a clean, safe, and cost-efficient non-carbon- and non-sulfur-emitting geothermal energy across Europe and the world, deploying different technologies.
- Project SUCCEED (Synergetic Utilization of CO_2 storage Coupled with geothermal EnErgy Deployment, 2019-2022), with demonstrators at Hellisheidi (Iceland) and

Kızıldere (Turkey). It aims to research and demonstrate the feasibility of using produced and subsequently vented CO_2 for reinjection to the reservoir to improve geothermal performance, while also storing the CO_2.

The corresponding pilots and demonstrators with their characteristics are presented in Table 8.

NEW ZEALAND initiative
Operators in New Zealand (Mercury Energy at Nga Tamariki, Contact Energy at Te Huka) have also begun to capture associated CO_2 for reinjection into the geothermal reservoir. New Zealand is another country where geothermal energy utilization can be associated with high greenhouse gas emissions, similar to that of natural-gas-fired power generation.

CO_2-DISSOLVED
The set of projects CO_2-DISSOLVED (2013-2016, ANR), PILOTE CO_2-DISSOLVED (2016-2017, GIS-Geodenergies), CO_2-DISSOLVED_INJECTION (2018-2020, GIS-Geodenergies), and GEOCO$_2$ (2018 – 2021, Centre-Val de Loire (France) regional funding) propose a new approach to CCS. Here, CO_2 is stored by dissolution in saline waters of a deep aquifer which is concomitantly used for geothermal exploitation (for heat supply, with a targeted temperature around 40-80°C). This concept was initiated and is currently led by BRGM (French Geological Survey) with involvement of national and international partners. Discussions are underway with French industrial companies interested in the CO_2-DISSOLVED concept, with a view to launching a demonstration project in the forthcoming years (the calendar is still uncertain). The project is included in Table 8 for comparison.

AATG / CLEAG
AAT Geothermae (AATG) is a project in Croatia, successively funded by the EC-NER300 programme (2014) and the EC Small-scale Innovation Fund (2020), which aims to produce heat and electricity from a 110°C geothermal brine containing a high volume of dissolved methane. In contrast to conventional geothermal power plants, this hybrid system uses two sources for its energy production: hot water as well as the natural gas dissolved in it. Methane is separated from the water and burned in a gas engine. The CO_2 from combustion, as well as any other non-condensable gas associated with the hot water produced to surface, is captured at a percentage of 98% and reinjected into the aquifer (personal communication).

Table 8. Pilot and demonstrators for water-driven geothermal heat extraction with CO_2 (re)-injection

	Projects [Industrial]	Depth (m)	T° (°C)	Injection (kt/year)	Main trapping mechanism	Description	Progress	Reference
Hellisheidi (shallow reservoir) [Iceland]	Carbfix GECO SUCCEED	500	20-50	**0.23 (obj: 2.2)** Dissolved	Mineral	The project demonstrated that 95% of the CO_2 can be mineralized as calcite in a shallow basaltic reservoir (20-50°C).	2012-2016	Matter et al., 2011, 2016; Snæbjörnsdóttir et al., 2020, etc.
Hellisheidi (deep reservoir) [Iceland]	Carbfix GECO SUCCEED [OR]	750	260	**12 (obj: 33)** Dissolved	Mineral	Flash-unit power plant. 303 MWe. Basaltic formations CO_2 content in the geothermal fluid: around **0.1%** The project demonstrated that 60% of the CO_2 can be mineralized in basaltic geothermal reservoir	Started in 2014	Gunnarsson et al., 2018; Sigfússon et al., 2018
Nesjavellir [Iceland]	GECO [OR]	1000-1700	200-300	**1** (test phase)	Mineral	Flash-unit power plant. Capacity of 120 MWe and 300 MWth. Basaltic formations. CO_2 content in the geothermal fluid: around **0.1%**	To begin in 2022	Galeczka et al., 2022
Ngatamariki and Te Huka [New Zealand]	[Mercury NZ]	Around 2500m	260-280°C	?	?	Reinjection of NCG	In development in 2022.	ThinkGeoenergy[4] BusinessDesk[5] Stuff[6]
Bochum Mule [Germany]	GECO	525 m	25		Solubility and mineral	The German demo site in Bochum is a test site in a sedimentary environment, not linked with a geothermal plant. It consists of a dual flow and injection system. Modelling results showed that carbon dioxide mineralization in the underground of the Bochum GECO site is basically possible (in the form of siderite mineral). These results are pending validation after the demonstration process.	In development in 2022.	
Kızıldere [Turkey]	GECO SUCCEED [Zorlu]	1500	200	**Kızıldere - II: 1** Dissolved **Kızıldere - III: 30** Supercritical	Structural and residual for Kizildere-III	Flash steam turbines. Capacity **Kızıldere** -III 165 MWe Metamorphic formation consisting of marble, quartzite, and schist. Liquid-dominated fluid, 10% steam. CO_2 content: around **1-4%**	In development in 2022.	Durucan et al., 2021; Gunnarsdóttir et al., 2021; Erol et al., 2022

4 https://www.thinkgeoenergy.com/successful-tests-of-capturing-and-reinjecting-geothermal-co2-nz/
5 https://businessdesk.co.nz/article/energy/mercury-presses-on-with-co2-reinjection
6 https://www.stuff.co.nz/environment/climate-news/129520035/geothermal-energy-is-already-reliable--soon-it-might-be-carbonneutral-too

						The injected CO_2 corresponds to a limited part of the CO_2 produced.		
Castelnuovo [Italy]	GECO [Storengy]	3500	280	**30** Liquid CO_2-water mixture	Structural and residual	Heat exchanger and ORC turbine Metamorphic steam dominated reservoir CO_2 content: around **8%**. Total NCG reinjection was targeted. Due to permitting issues, is was replaced by the Hveragerði site	Stand-by.	Gunnarsdóttir et al., 2021; Niknam et al., 2021
Hveragerði [Iceland]	GECO [OR/ISOR /Storengy]	Storengy (STY) is collaborating with the Iceland GeoSurvey (ISOR) to develop the closed-loop test unit and demonstrate it in a 200°C well in Hveragerði, Iceland. To simulate similar reservoir conditions as in Castelnuovo, the geothermal fluid will be supplied with a CO_2 tank and steam.					In development in 2022.	
Paris basin [France]	CO_2-DISSOLVED	1600-1800	60-80	**Obj:45** Dissolved	Solubility	Heat exchanger for District heating Network Sedimentary basin. CO_2 from external source, injected at **~1.5%**	In preparation	Kervévan et al., 2014, 2017
CLEAG demonstrator [Croatia]	NER 300 [AATG, CLEAG]	1850	110	**60** Dissolved	Solubility	The geothermal fluid contains notably CO_2 and CH4. Methane is used in a gas engine. Heat from geothermal fluid is valorized. Reinjection of CO_2 from the fluid and from the combustion at a rate of **0.6%** by mass (water flow: 320kg/s)	Initial testing in 2014	http://aatg.energy/

These projects are distinct but present some similarities. In order to explore the concepts in this study, we considered the following categorization (Table 9):

- Geothermal heat extraction that generally co-produces non-condensable gases (NCG) (notably CO_2) with the water phase, in geological environments that favour rapid mineralization (e.g. basalts), where CO_2 is reinjected in dissolved phase in water (stemming from the geothermal reservoir or from external source), for rapid mineralization in the geothermal reservoir. This corresponds to the demonstrator sites of Hellisheidi (shallow and deep reservoir) and Nesjavellir (Iceland). It is the initial CarbFix concept, further developed within GECO and SUCCEED. It is also developed in New Zealand at the Ngatamariki and Te Huka geothermal sites.

- Geothermal heat extraction that co-produces NCG (notably CO_2) with the water phase, where CO_2 is reinjected in dissolved or supercritical phase in the original geothermal brine, with mainly structural and solubility trapping in the geothermal reservoir. This corresponds to the demonstrators of Hveragerði (Iceland), Kızıldere (Turkey), and Castelnuovo (Italy). It is notably developed within GECO and SUCCEED.

- Geothermal heat extraction that doesn’t co-produce significant quantities of NCG (notably CO_2), where CO_2 from an external source is injected in dissolved phase in the geothermal reservoir, mainly for solubility trapping. This corresponds to the CO_2-DISSOLVED project .

- Geothermal heat extraction that co-produces methane and possibly NCG (notably CO_2) with the water phase, where both hot water and methane are used for cogeneration, with capture of CO_2 from combustion, and CO_2 injection in dissolved phase, with mainly solubility trapping in the geothermal reservoir. This corresponds to the demonstrators of AATG (CLEAG technology, Croatia).

From the main features presented in Table 9, other concepts could be elaborated, merging different properties and objectives. We introduce two supplementary concepts in this section, presented in the literature in conceptual articles (with no feasibility study or pilot):

- A first one that focuses on a power plant where CO_2 capture is deployed. In order to avoid energy penalty stemming from capture, the authors investigate the possibility to use the energy contained in the geothermal fluid (heat and methane content) for capture and the possibility to dissolve the captured CO_2 in the geothermal fluid.
- A second one, called geothermal BECCS (BioEnergy–CCS), that combines a biomass/geothermal power plant (that produces energy with geothermal energy for pre-heating and biomass combustion) with capture of CO_2 from combustion, and injection of the captured CO_2 in dissolved form in the geothermal fluid in order to perform CCS.

For coherence, in the following sections, the concepts will be referred to using the designations introduced in Table 9.

Table 9. Concepts categorization

	Geothermal fluid characteristics	Origin of the CO_2 stored	Injection form	Trapping mechanism in middle term	Sizing of services	Philosophy
"Carbfix-like" concept	Might contain NCG/CO_2	Generally geothermal-fluid (or external origin)	Dissolved in external fluid (e.g. seawater)	**Mainly mineral**	Sizing imposed by **large-size** geothermal power plants (~ 100-300 MWe) Quantity of CO_2 derives from the fluid content (~0.1%)	**CCS-driven concept at origin, dual objective then**
CO_2-reinjection concept	**Significant content of CO_2 and other NCG**	Geothermal fluid	Dissolved in the geothermal fluid **Liquid or Supercritical**	Mainly solubility Mainly structural	Sizing imposed by medium or **large-size** of geothermal power plants (~ 5-200 MWe) Subsequent quantity of CO_2 derives from the fluid content (up to 8%)	**Towards zero-emission geothermal power plant**
"CO_2-DISSOLVED-like" concept	**Low natural CO_2 content**	**External origin**	Dissolved in the geothermal fluid	Mainly solubility	Sizing operates a balance between requirements for heat production (order of magnitude 5 MWth) and opportunities for external CO_2 storage.	**Dual objective**
"CLEAG-like" concept	**Significant content of methane (and possibly NCG)**	Geothermal fluid and methane combustion	Dissolved in the geothermal fluid	Mainly solubility	Sizing imposed by medium-size geothermal power plants (20 MWe - 80 MWth) Subsequent quantity of CO_2 derives from the fluid content.	**Towards zero-emission geothermal power plant**
Geothermal-BECCS concept	/	**External origin, more precisely from bioenergy production**	Dissolved in the geothermal fluid	Mainly solubility	Scalable sizing, e.g. 100 MWe, with geothermal and biomass energy sources.	**Improvement of BECCS concept (biomass energy production & CCS)**
CCS-driven concept to compensate capture energy requirements	**Significant content of methane**	**External origin**	Dissolved in the geothermal fluid	Mainly solubility	**Large-size (500 MWe)** imposed by the CCS objective: produce sufficient quantity of water to dissolve CO_2 and recover energy required for capture process.	**CCS-driven concept: use geothermal to compensate energy capture requirements**

3.2.2 *CarbFix-like concept*

Description

The CarbFix concept stems from a CCS concept. The original idea targets CO_2 storage through injection into reactive rocks (such as mafic or ultramafic lithologies), provoking CO_2 mineralization and, thereby, it is argued, permanently fixing carbon with negligible risk of return to the atmosphere (Gíslason et al., 2018; Snæbjörnsdóttir et al., 2020). The concept was primarily developed in Iceland where the geological characteristics are highly favourable. The Icelandic context is also favourable for high-temperature geothermal heat extraction. Since the extracted steam contains CO_2, the CO_2 used for concept demonstration was extracted from the existing geothermal power plant.

As illustrated in Figure 24 (left), the CarbFix concept essentially relies on injecting CO_2, onshore or offshore, into reactive rocks. The CO_2 stems from a concentrated “emission source”, which might be separated at a wellhead or at a geothermal power plant. But other sources are possible, such as a Direct Air Capture (DAC) unit, or any, even remotely located industrial source (e.g. Etcheverry et al., 2021). The required water comes from seawater or groundwater (e.g. condensates from a geothermal power plant). Another similar concept targeting storage through rapid mineralization has been demonstrated in the USA at the Wallula demonstration site. The difference is that CO_2 is injected in supercritical or liquid form. More information can be found in Snæbjörnsdóttir et al. (2020).

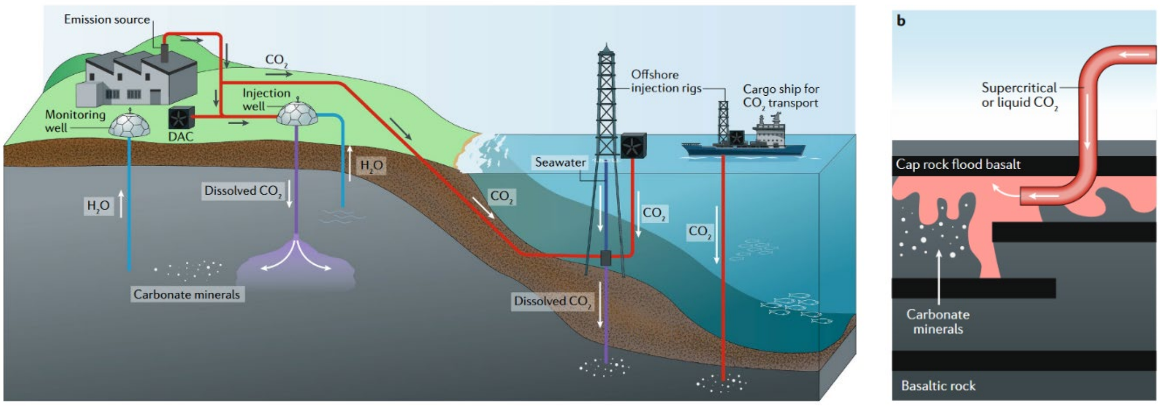


Figure 24. Left: Illustration of the CarbFix concept (not necessarily correlated with geothermal activity). Right: illustration of the Wallula demonstration site (Washington, USA). (Snæbjörnsdóttir et al., 2020)

The idea of the CarbFix concept is to promote mineral carbonation as rapidly as possible in order to guarantee permanent and safe CO_2 storage. Carbonation is a natural process that generally occurs over the long term (~10,000 years). The process can be accelerated by targeting reactive rocks, such as mafic or ultramafic lithologies, which contain high concentrations of divalent cations, such as Ca^{2+}, Mg^{2+} and Fe^{2+}. Water containing dissolved CO_2 is acidic (i.e. carbonic acid), with a typical pH of 3–5, which yields to rapid dissolution of silicate minerals such as pyroxene, a common mineral in basalt and peridotite, notably releasing the above-mentioned cations. After dissolution, the reaction with dissolved CO_2 produces calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) or magnesite ($MgCO_3$). To accelerate the process even more, it is proposed to inject CO_2 directly in dissolved form, achieving solubility trapping immediately (Sigfusson et al., 2015) and mineral trapping over 95% within 2 years at limited temperature (20–50 °C) (Saldi et al., 2009; Matter et al., 2016; Pogge von Strandmann et al., 2019). Other important factors for efficient subsurface carbon mineralization are the permeability and/or active porosity of the host-rock formation (Snæbjörnsdóttir et al., 2020).

The concept has been widely investigated, as highlighted by the high number of scientific papers (exhaustive list available at: https://www.carbfix.com/scientific-papers). The geochemistry of such systems is widely addressed in the literature. Impacts of geochemical reactions on porosity and possible operational issues (clogging) has been investigated with reassuring results (e.g. Snæbjörnsdóttir et al., 2018). Laboratory experiments have allowed a better understanding of the process.

Within this study, we focus on hybrid use and thus consider applications of the concept to improve environmental performance of geothermal exploitation. CarbFix has been regarded as a flagship concept for some years and further investigated in projects such as the European project GECO that aims at improving environmental performance of geothermal energy production.

Hellisheidi industrial demonstrator site

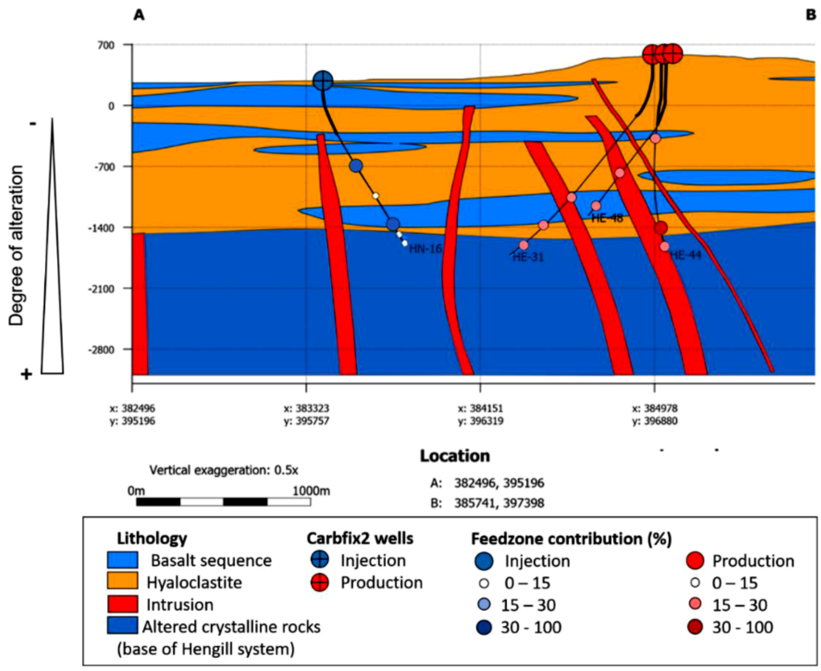


Figure 25. Illustration of the CarbFix demonstration site at Hellisheidi (Ratouis et al., 2022)

Following the success of the initial CarbFix project in Hellisheiði (started in 2012, at temperatures around 20-50°C and with a limited injected quantity of CO_2), the project was upscaled in 2014 to target a hotter and deeper reservoir (Gunnarsson et al., 2018; Sigfússon et al., 2018). The gases (CO_2 and H_2S) are captured directly from the geothermal power plant and dissolved in the condensed steam from the power plant turbines. The water containing dissolved CO_2 and H_2S is then injected at a depth of ~800 m into the basaltic reservoir at temperatures of ~250 °C. With this upscaled system, over 50% of the injected carbon is fixed as carbonate minerals within months of injection.
The Hellisheiði power plant started operation in 2006 and produces 303 MWe and 133-200 MWth energy (Sigfússon et al., 2018; Durucan et al., 2021) with 61 production and 17 reinjection wells at depths from 1,500 to 3,300 m. Regarding fluxes and ratios, different figures are presented in the various articles. While this is fully understandable, in view of the progressive evolution of the plant and the non-continuity of operations as a demonstration site, it leads to different extrapolations of assumptions. The figures presented below should thus be considered as ballpark figures (Gunnarsson et al., 2018; Durucan et al., 2021):

- CO_2 and H_2S fluxes:

  - the Hellisheiði power plant emits around 40,000 t CO_2 annually (1.3 kg/s), and 12,000 t of H_2S (0.4 kg/s);
  - the project currently captures and stores ~33% of the CO_2 emissions with the aim to increase injection to ~90% of the CO_2 from the plant before 2030. It stores around 68% of H_2S emissions.
  - the mass flow of CO_2 produced in geothermal wells decreases with time in the geothermal production wells from 1.4 kg/s to 1.1 kg/s of CO_2 between 2014 and 2017. (Sigfússon et al., 2018).
  - The CO_2 reinjection rate corresponds to around 0.2-0.4 kg/s.
- Water fluxes:
  - The water flow rate for geothermal exploitation is around 1056 kg/s (for several production wells).
  - The CO_2 flux injected in the dissolved form requires water flows of around 15-130 kg/s (Gunnarsson et al., 2018). The water retrieved for CO_2 injection is thus limited. The major part of brine is reinjected directly in the geothermal well.

Study of potential indicates that “the storage potential of the reservoir is not a limiting factor for the on-going operations” (Sigfússon et al., 2018).

Falling within CCS-concepts, risks and impacts have been rigorously studied for the CarbFix concept (e.g. Snæbjörnsdóttir et al., 2018): the risk of leakage is reduced as CO_2-charged water is denser than the corresponding CO_2-free water, noting the absence of any supercritical buoyant phase; the major drawback is that a large quantity of water is needed to dissolve the CO_2 gas, but pairing CarbFix with geothermal exploitation brings a cost- and environmentally-effective solution to water availability (the mass ratio of water quantity over CO_2 quantity varies depending on the CO_2 purity, the best achievable ratio being 22 for pure CO_2; a ratio of 25 appears feasible); seismic risk is managed by continuous monitoring and adjustment of injection rates; risk of groundwater contamination needs to be managed according to the hydrogeological context.

Little information is available on the CarbFix business model. The Hellisheidi site, as the first industrial demonstrator site, should not be considered as representative of the technology costs. Estimates for operating costs are provided in Gunnarsson et al. (2018) who suggest 24.8 US$/t, not including investment costs, but these costs relate to the CCS objective and not to the geothermal energy production objective.

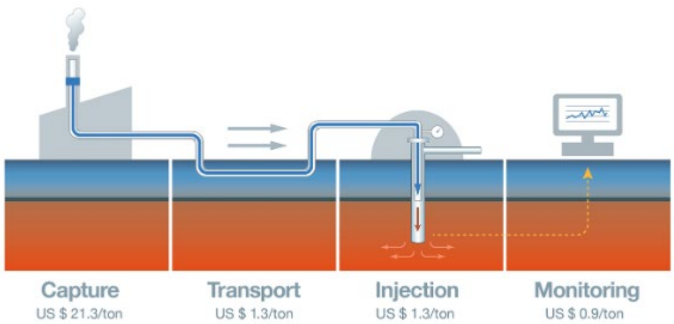


Figure 26. Illustration of the operating costs at the CarbFix site (assuming existing infrastructures) (Gunnarsson et al., 2018)

Nesjavellir industrial demonstrator site

This second industrial demonstrator site is planned to be deployed in 2022 (Galeczka et al., 2022). The geological features are similar, with alternating successions of hyaloclastites, lava sequences and intrusive rocks. At the target injection depth of 1000–1700 m below the surface, the permeability is dominated by fractures. The geothermal fluids at the reservoir depth have temperatures in the range of 200-300°C.

The geothermal power plant at Nesjavellir has operated since 1990 with an installed capacity of 120 MWe and 300 MWth. Emissions of the order of 15 kt/y of CO_2 and 8 kt/y of H_2S.
The system will be tested with the injection of 1 kt/y of CO_2 and 0.4 kt/y of H_2S.
Both field observations and model results suggest that higher temperatures may be less favourable to mineralization.

For the concept presentation in the table below, we use mostly figures available from Hellisheidi and extrapolate figures to the evolution planned in 2030.

Variations

In September 2022, a variation of the CarbFix concept was announced in New Zealand[7]. The concept consists of capturing NCG naturally present in the geothermal fluid and to reinject them via the reinjection well. In order to favour CO_2 mineralization in the absence of the favourable geological features available in Iceland, "the plan is to inject ions along with the reinjected gases that will cause them to petrify into common and non-toxic minerals – CO_2 into calcite, and H_2S into pyrite".
It should be noted, however, that this concept differs from a geochemical point of view. Taking into consideration the crucial role of the geochemical reactions in such solution, a profound geochemical investigation is needed in order to show its basic feasibility.
This concept can be classified either with the Carbfix-like concept or with the CO_2-reinjection concepts (we chose the former).

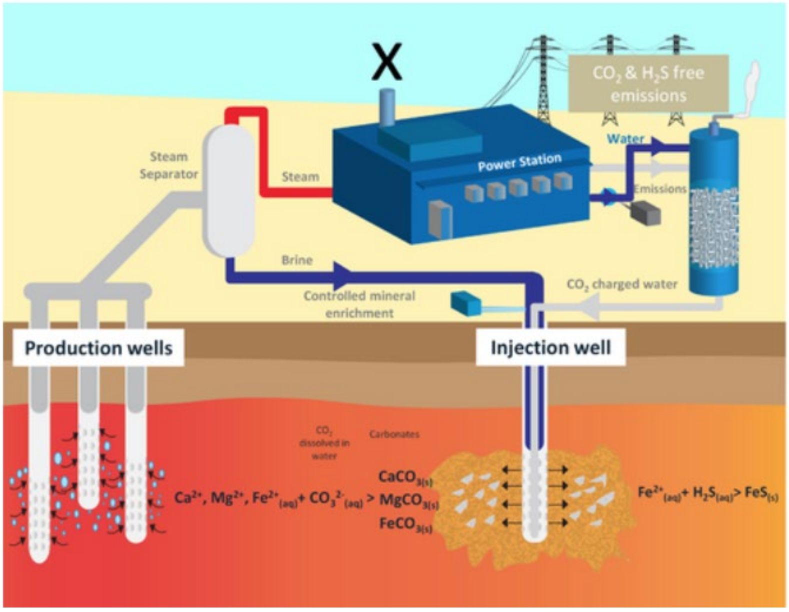


Figure 27. Illustration of the geothermal concept in New Zealand that targets rapid mineralization as in Iceland (University of Auckland)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS	
Geology and petrophysical properties	The concept needs mafic or ultramafic lithologies (basalt sequence, hyaloclastites, dyke intrusions, faults basaltic rocks) or sedimentary rocks as in the concept from New Zealand. Storage formation consists of porous matrix and fractures.

[7] https://www.thinkgeoenergy.com/nz-geothermal-institute-receives-funding-for-greenhouse-gas-capture-project/ , accessed 20th of September 2022.

	Porosity Permeability	[5-10] % [10^{-13}-10^{-12}] m² (Snæbjörnsdóttir et al., 2018)
Depth	Range [0.7-2] km	
Dimensions	Thickness Extension	[500-700] m Kilometre scale - Lateral extension [1-2] km
Temperature	[200-300] °C	
ENGINEERING		
Wells	At least one production well and one reinjection well. Well fields include 61 production and 17 reinjection wells at Hellisheidi. Well design requirements: Generally vertical wells, suitable for dissolved CO_2 and for high temperature (200-300°C) Inter-well distance: [1000-1500] m	
Surface installations	Flash-unit power plant Fluid pre-processing facilities (separator, scrubber, etc.) Facilities for injection in dissolved phase	
Geothermal fluid	Flux of geothermal brine around 1000 kg/s (in the assumption of several wells) NCG in the geothermal brine: around 0.1% by mass Flux of CO_2 around 1 kg/s, injected in the dissolved form	
INTEGRATION		
Upstream	No CO_2 requirements from external source.	
Downstream	Requirements: • Electricity production: connection to suitable voltage grid • If possible: local valorization of co-produced heat (if Combined Heat and Power production to optimize efficiency)	
SERVICES PROVIDED		
Net baseload electricity production	Electricity production: around 300 MWe	
CO_2 geological storage	The order of magnitude of avoided* CO_2 emissions is 10-40 kt/y, i.e. 0.3-1.2 Mt over 30 years. * by comparison with a geothermal power plant exploited with current practice, with gases released to the atmosphere.	
FROM CONCEPT TO MARKET		
Readiness	First pilot tests initiated in 2011. Industrial demonstrator started in 2014. New demonstrator to begin in 2022. Both demonstrators in Iceland. Numerous scientific articles.	
Proponents	This technology has been pushed by a group of Icelandic partners. Several other European countries involved notably through European projects.	
Availability of economic consideration	Limited information	

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

This technique claims permanent storage of CO_2. The fact that fast mineralization processes actually occur makes this assumption very credible at first sight. However, we probably lack experience on long-term and large-scale dissolved CO_2 injection in basalts to confirm this. So far, only relatively small amounts of CO_2 (a few tens of kilotons per year) have been injected and the viability of upscaling to a few hundreds to millions tons of CO_2 per year still needs to be proven. In particular, the nature of the basaltic reservoir is likely to be significantly modified in the areas where CO_2 mineralization occurred, with possible consequences on long-term injectivity. One can wonder about the impact on the accessibility to the cation-provider mineral phases if carbonates cover the basaltic porous matrix as well as on the consequences of porosity variation on permeability and thus injectivity. The question is then not only how much CO_2 can be stored but where will it be stored in the reservoir and for how long can it be injected by the same wells. This requires detailed 3D reactive transport modelling investigations in order to assess the space-time geochemical and hydrodynamic evolution of the reservoir over long periods of injection. To our knowledge, this modelling work was not done yet.

3.2.3 *CO_2-reinjection concept – dissolved or supercritical*

Description

The concept here is to capture CO_2 emitted during geothermal exploitation (and not the emissions of an external emitter). When operating a geothermal doublet, the native fluid pumped might contain NCG such as CO_2, NH_3, N_2, CH_4, H_2S, and H_2, and common practice is to release these gases into the atmosphere.

In some geological contexts (e.g. Turkey, Iceland, Italy, New Zealand), the geothermal fluid has a significant CO_2 content and the life cycle assessment (LCA) performance of geothermal plants is significantly penalized by these NCG. Depending on the geothermal fluid source, the fraction of NCG can vary from less than 0.2% to more than 25% by weight of the geothermal fluid (Ozcan and Akkurt, 2010). The global average emission factor for geothermal projects is 121 g/kWh (Akin et al., 2020) but for a number of sites in Turkey and Italy, GHG emissions from geothermal power plants can be higher than 500 g/kWh and in some cases higher than emissions from coal-fired power plants (Ármannsson, 2003; Fridriksson et al., 2017). The origin of these emissions and their evolution with time are described in Akin et al. (2020) and Fridriksson et al. (2017).

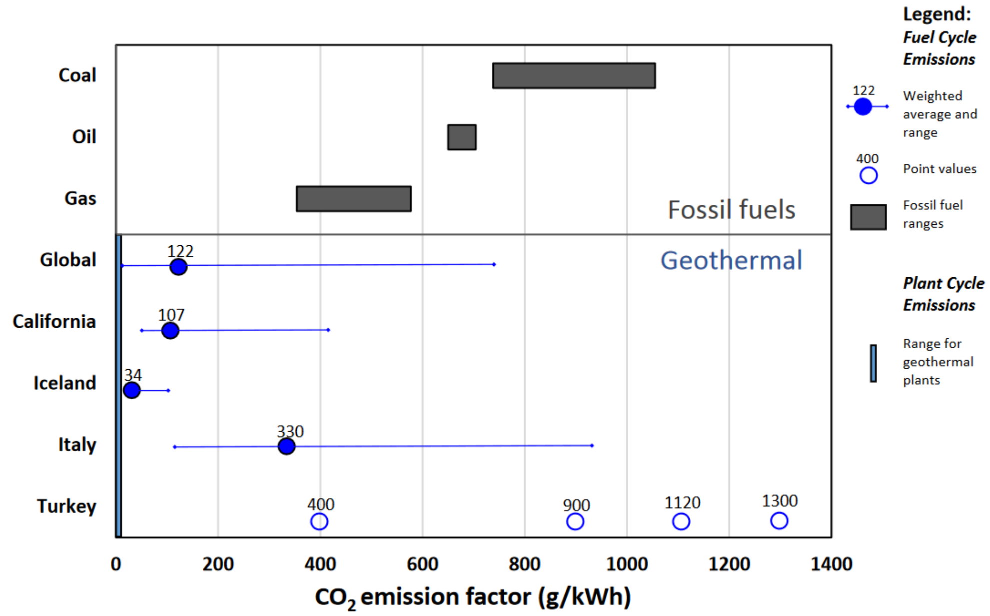


Figure 28. Weighted average and range of emission factors from geothermal power plant compared with coal, oil and gas power plants (Fridriksson et al., 2017)

Reinjection of produced CO_2 back into the geothermal fields has thus been proposed for sites with high NCG content (Bonafin et al., 2019; Durucan et al., 2021). The philosophy is to produce geothermal renewable energy with near-zero emissions. The CO_2 (and other NCG) storage is a sub-part of the geothermal energy system. This is an important difference compared to the CO_2-DISSOLVED concept that deals with an external CO_2 flux and requires rather CO_2-poor geothermal waters.
The concept is currently being investigated in several projects, with demonstrators that have just begun operations or are still in preparation. Experience, feedback and guidelines will probably be published soon, and upcoming results should allow progress and better practical definition of the concept in future years.

Regarding the injection form:
The first option is to reinject NCG entirely dissolved in the geothermal fluid. It enhances solubility trapping, prevents geomechanical damage due to overpressure, and avoids risk of gas leakage from the reservoir. The technical challenges raised by injection in the dissolved form can technically be addressed, as demonstrated within the CarbFix project. However, considering the high NCG ratios, solubility might be a problem for total reinjection. As illustrated in Figure 29, the solubility depends notably on depth, temperature and brine salinity. The order of magnitude for solubility is between 2 and 6% of CO_2 by weight in the water phase. In some cases, the CO_2 production mass rate is higher than the solubility rate. This is explained by production of a two-phase flow (liquid and vapour) or a steam flow. Thus it is not always possible or physically feasible to dissolve the totality of the reinjected CO_2. In such cases:

- A liquid brine-CO_2 mixture can be reinjected. It presents intermediary performance in terms of geomechanical and leakage risks. (Kaya and Zarrouk, 2017)
- CO_2 can be reinjected in supercritical form in a distinct well. The buoyant-free phase should be managed cautiously. Containment should be guaranteed by an efficient caprock.

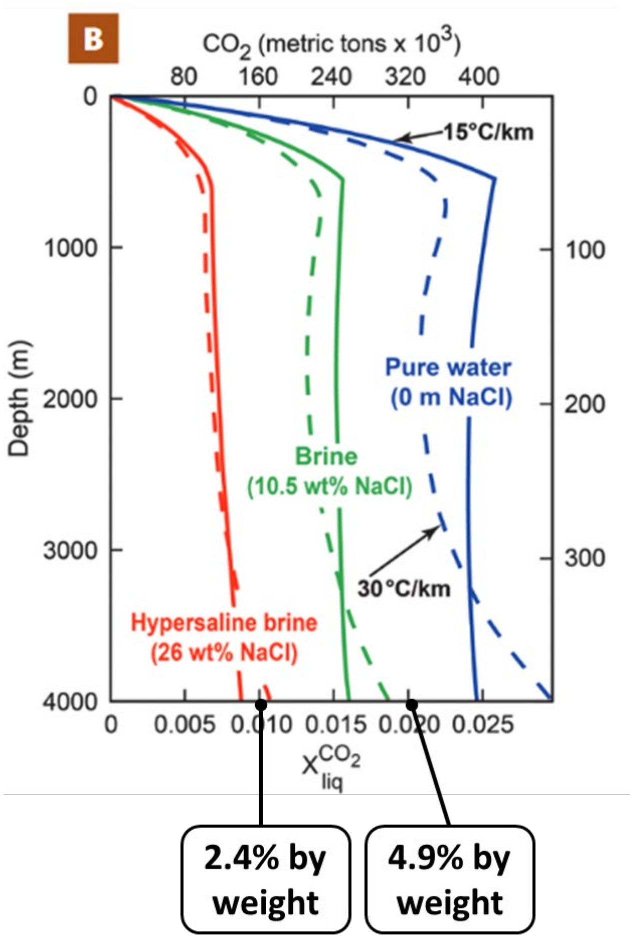


Figure 29. Solubility (mole fraction, x) of CO_2 in a NaCl solution as a function of depth and salinity for two geothermal gradients. Modified from Benson and Cole (2008)

Apart from the CarbFix project, NCG reinjection has already been tested for geothermal reservoirs in a few fields including Hijiori, Ogachi (Japan), Coso (USA), and Puna (Hawaii) (Kaya and Zarrouk, 2017).

On current demonstrators:
Several projects have been recently proposed to demonstrate the concept, one in Turkey, one in Italy (but on stand-by due to permitting issues) and one in Iceland to replace the Italian one.

Demonstrator at Kızıldere (Western part of Turkey), within the projects GECO and SUCCEED. The Kızıldere geothermal field is Turkey's first high-potential geothermal field explored for energy generation. Three power plants (flash steam turbines) are in operation with the following capacities: Kızıldere-I 15 MWe (commissioned in 1984), Kızıldere-II 80 MWe (commissioned in 2013), and Kızıldere-III 165 MWe (commissioned in 2018). For the three plants, there are 38 production and 24 reinjection wells drilled at depths from 500 to 3,500 m (Durucan et al., 2021). The geothermal fluid is a two-phase liquid-dominated fluid produced at a rate of 1389 kg/s (5000 t/h). According to Gokcen et al. (2004), the field is a liquid-dominated system with a steam fraction of 10–12%. The NCG content in the steam is around 10-21% by weight (mainly CO_2 – 96-99%). We can thus estimate the CO_2 flux around 1-2% by weight. Additional CO_2 dissolved in the liquid phase should also be considered. According to Durucan et al. (2021) the concentration of CO_2 can reach up to 4% by weight depending on site characteristics. Considering a CO_2 mass fraction between 1 and 4%, the order of magnitude for the CO_2 flux produced is thus around 15-55 kg/s.

Considering the high NCG content in the natural geothermal fluid, several solutions are under investigation:

i. Within the GECO project, some gas from Kızıldere-II is sent to a CO_2 facility (Linde gas) that processes CO_2 for commercial activities. It can process around 3 kg/s (240 t/day[8]).
ii. Within the GECO project, CO_2 injection in dissolved phase will take place for six months with a weight fraction of 0.11% (0.06 kg/s and in total 950 ton of CO_2 in 6 months) (Gunnarsdóttir et al., 2021) (see Figure 30).
iii. Within the SUCCEED project, an existing well will be used to inject CO_2 into the reservoir in supercritical state for Kızıldere-III. The flux will be retrieved from the Linde Gas facility and will correspond to around 1 kg/s (80 t/day).

It should be noted that the current reinjection of CO_2 is an order of magnitude lower than the CO_2 produced by the geothermal power plant.
In the present study, we do not consider the first solution (no underground reinjection) and focus on the latter two. This is aimed at enhancing the pressure in the reservoir as the driving mechanism for the geothermal fluid and improving geothermal performance, as well as storing the produced CO_2, providing a low environmental impact and resource-efficient coupled geothermal-CCUS technology. The corresponding geothermal reservoir is a high temperature (around 200°C) deep (around 1500 m) metamorphic formation consisting of marble, quartzite, and schist. The reservoir is faulted and fractured and overlain by a caprock with high clay content. The porosity of the reservoir rock is estimated to be around 3% in the matrix and in fractures, with permeability estimated around 10^{-15} m² in the matrix and between $7x10^{-14}$ and $2x10^{-15}$ m² in the fractures (Erol et al., 2022).

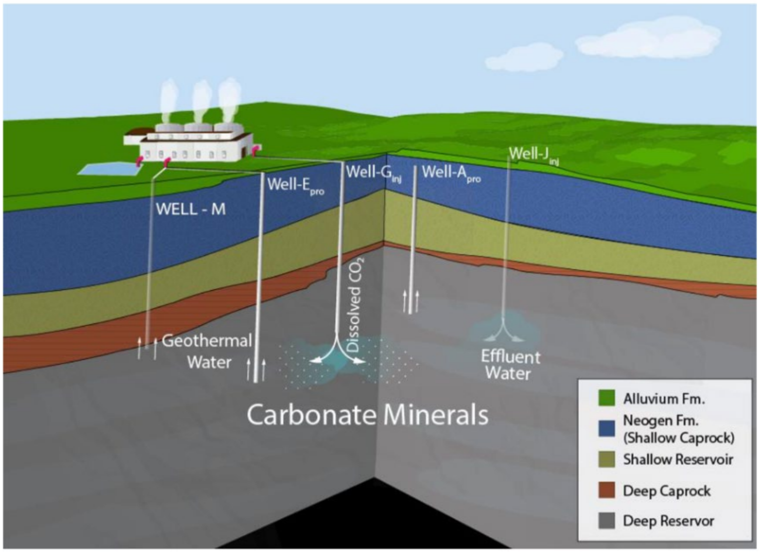


Figure 30. Illustration of the CO_2-reinjection concept (Erol et al., 2022)

Demonstrator at Castelnuovo (Tuscany, Italy), within the GECO project. The objective of the Castelnuovo demonstrator was to demonstrate the feasibility of the total geothermal fluid reinjection (including NCGs). The configuration consists of two production and one reinjection wells. The field is a metamorphic (micaschist), steam-dominated geothermal reservoir. In the Italian context, as reported by Bidini et al. (1998), steam may be available with a temperature of about 200°C, with a NCG content ranging from 4 to 10% by weight. For Castelnuovo, the resource condition is expected to be saturated vapour at a pressure of 60 bar and a temperature of 280°C at about 3500-m depth (Niknam et al., 2020). The geothermal fluid flow rates used in simulations presented in Niknam et al. (2020) are around 12 kg/s for brine and 1 kg/s for CO_2. The heat extraction power is around 26 MWth, and electricity is produced

[8] https://www.imperial.ac.uk/energy-futures-lab/succeed/research/pilot-sites/kizildere/

through a heat exchanger and an ORC turbine, yielding around 5 MWe. The NCG mass content is estimated at 8% (7.8% CO_2 and 0.2% H_2S). The separated CO_2 should be compressed, liquefied and mixed with the geothermal condensate prior to reinjection. More detailed information are available in Gunnarsdóttir et al. (2021). Due to permitting issues, the project is currently on stand-by.

Demonstrator at Hveragerði (Iceland), within the GECO project. It replaces the Castelnuovo demonstrator and will demonstrate injection feasibility. However, since the Icelandic geothermal fluid contains less CO_2, the geothermal fluid will be enriched with additional CO_2 from external tanks. The geological features of this demonstrator are different from those of Castelnuovo, with underground phenomena probably being more similar to Hellisheidi or Nesjavellir.

On other studies:
Other modelling studies should be mentioned:

- Kaya and Zarrouk (2017) investigated through numerical study the feasibility of reinjecting H_2S and CO_2 into a geothermal reservoir, after capture and dissolution in effluents from the geothermal field (estimated reservoir parameters: porosity 5%, permeability 17x10^{-15} m², reservoir temperature around 300°C, reinjection temperature 170°C, brine flow in the range 130-215 kg/s, 2.5% by mass CO_2 in the reinjected fluid). They study the impact of reinjection on energy recovery, on trapping mechanisms, and on NCG breakthrough into production wells. Their work highlights the following challenges for deployment of the concept:
    - Formation of gas phases at lower pressures (e.g. due to pressure drop caused by production) and/or the shallow subsurface requires careful consideration of the injection rate and composition of NCG. The risk of leakage to the surface is very limited if the injected NCG remain in the liquid phase but increases in the case of formation of a gas or supercritical phase.
    - The numerical results show that modelling, monitoring and careful siting of wells are required to prevent premature breakthrough of injected fluid and NCG to the production wells, highlighting the design challenges.

- Erol et al. (2022) performed predictive 3-D reactive transport modelling using TOUGHREACT for a case study similar to the Kızıldere demonstrator. The aims of the study are the evaluation of dynamic fluid-rock interactions and characterization of the mineralization processes. The brine flux is around 50 kg/s. The CO_2 injection rate is comprised between 0.02 and 0.13 kg/s. The results indicate that the fluid remains stable as a single-phase and that the mineralization process is limited. The calculated maximum injectable amount of CO_2 is 0.25% by weight to keep a stable single-phase. This value is largely below the mass flow rate in the produced fluid. Thus total reinjection in the dissolved phase would not be possible. Their work highlights the following challenges for deployment of the concept: one of the major concerns about reinjection of the captured CO_2 is to predict the geochemical interaction between the injected fluid-CO_2 and the bedrock, and the corresponding alterations due to reinjection on the reservoir parameters. According to their results, porosity alteration in the vicinity of the pilot injection well is controlled by dissolution and precipitation of quartz, with a crucial role played by injection temperature. This concern was addressed in a recent experimental work by Mountain (2022). The work shows that CO_2 reinjection can have a positive geochemical effect in the reinjection wells and the nearby formation, by significantly reducing the precipitation of silica scaling in the wells.

- Bonalumi et al. (2017) simulated a geothermal reservoir (with high NCG content) and the flash power plant for two different surface layouts: a conventional layout where the CO_2 is separated and compressed after the condenser; a flash plant layout that allows

separation of the CO_2 at higher pressure than in the conventional layout, thus reducing the requested power consumption. The case study corresponds to a depth around 1000 m, with reservoir pressure around 10 MPa. Several values of reservoir temperature are tested (150°C, 175°C and 200°C) and two values of CO_2 content (1% and 5%). The geothermal flow rates are between 45 and 145 kg/s, and the net electricity power between 0.9 and 5 MWe. Their work highlights the following challenges for deployment of the concept:
  - For the injection of liquefied CO_2-brine mixture, the compression ratio required is high and the energy consumption of the compressor significantly affects the net power production. Alternative installation layouts are proposed to solve this issue (Bonalumi et al., 2017), with ambivalent conclusions.
  - The performance of investigated layouts are highly affected by the concentration of the carbon dioxide present in the reservoir, thus the design of the system should consider this parameter with caution.

- Niknam et al. (2020, 2021) also modelled surface equipment design, but for a binary cycle geothermal power plant (ORC turbine) including facilities required for the power cycle and the complete reinjection process of two-phase geothermal fluid. The case study corresponds to the vapour-dominant Larderello area in Italy.

- Salimi and Wolf (2012) investigated numerically the injection of CO_2 in a case study corresponding to the Delft Sandstone formation in The Netherlands at 2 km depth (reservoir temperature 80°C, injection rate 41 kg/s). The injected CO_2 fraction is comprised between 5 and 10%. As the CO_2 fraction increases between 7 and 10%, a gas phase (supercritical CO_2) is formed at the injection side (i.e., two-phase injection). It should be noted that this scientific article is not directly an illustration of the reinjection concept. The origin of CO_2 is not mentioned. It is a scientific contribution at a crossroad between the CO_2-DISSOLVED concept (CO_2 probably coming from an external source) and the reinjection concepts. Their work highlights the following challenges: permeability and porosity heterogeneities in a geothermal aquifer significantly influence both heat extraction and CO_2 storage.

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

<table>
<tr><th colspan="3">UNDERGROUND CHARACTERISTICS</th></tr>
<tr><td rowspan="2">Geology and petrophysical properties</td><td colspan="2">The concept targets any geothermal reservoir with high NCG (notably CO₂) content, e.g.:
- metamorphic carbonate in Turkey (marble, quartzite, schist)
- metamorphic micaschist in Italy
The geothermal reservoir consists of permeable matrix and/or permeable fracture/faults.
If injection leads to formation of a supercritical/gas phase, a caprock should guarantee the containment (e.g. clay layer).</td></tr>
<tr><td>Porosity
Permeability</td><td>[3-10] %
[10⁻¹⁵-10⁻¹⁴] m²</td></tr>
<tr><td>Depth</td><td colspan="2">Range [1.5-3.5] km</td></tr>
<tr><td>Dimensions</td><td>Thickness
Extension</td><td>Variable
Kilometre scale - Lateral extension [1-2] km</td></tr>
<tr><td>Temperature</td><td colspan="2">[150-300] °C</td></tr>
</table>

ENGINEERING	
Wells	The number and layout of wells varies, depending on the project size (e.g. tens of wells in Turkey, 3 wells in Italy). Well design requirements: Generally vertical wells, suitable for high temperature (150-300°C), and CO_2 reinjection.
Surface installations	Steam turbine or heat exchanger and ORC turbine Fluid pre-processing facilities (separator, scrubber, etc.) Facilities for injection in dissolved or mixture or supercritical phases, depending on projects characteristics.
Geothermal fluid	Variable flux of geothermal brine: around 1000 kg/s for the Turkish demonstrator, around 12 kg/s for the Italian pilot project. NCG in the geothermal brine: Several percent (between 1 and 8% by mass for the afore-mentioned demonstrators). Flux of CO_2 in produced fluid: variable (around 10-30 kg/s for the Turkish demonstrator, around 1 kg/s for the Italian pilot project). Injection rates for current demonstrators are around 1 kg/s, this corresponds to total reinjection for Italian context and to very partial reinjection for the Turkish concept at the moment. If the ratio CO_2 flux/brine flux is limited, injection can be done in dissolved form. Otherwise, CO_2 is injected in a brine-liquid mixture or in supercritical form.
INTEGRATION	
Upstream	No CO_2 requirements from an external source.
Downstream	Requirements: • Electricity production: connection to suitable voltage grid • If possible: local valorization of co-produced heat (Combined Heat and Power production to optimize efficiency)
SERVICES PROVIDED	
Net baseload electricity production	Electricity production: variable (around 200 MWe for Turkish power plant, around 5 MWe for the Italian pilot project)
CO_2 geological storage	The order of magnitude of avoided* CO_2 emissions is 10-600** kt/y, i.e. 0.3-18 Mt over 30 years. * by comparison with a geothermal power plant exploited with current practice, with gases released to the atmosphere. ** 600 kt/y corresponds to a high order of magnitude assuming total reinjection for a power plant such as Kizildere (currently less than 10% of produced CO_2 is reinjected)
FROM CONCEPT TO MARKET	
Readiness	The concept has been discussed for several tens of years. It is currently being thoroughly demonstrated and deployed (demonstrators to be launched in 2022-2023). The number of scientific articles is limited at the moment (10-20).
Proponents	The most active institutes working on this concept are Turkish, Icelandic and Italian, due to the existence of geothermal power plants with high NCG content in these countries.
Availability of economic consideration	Limited information

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

Any natural geothermal system where natural CO_2 content in brine is high will discharge CO_2 in its natural features. When a power plant is present in sites, this process is accelerated, CO_2 emerges from the deep at a constant rate. In general, reinjection of CO_2 will alter the total CO_2 in the geothermal system, although in most areas it will take many years for the change to become apparent. A first consequence is that natural emissions will change. Another consequence is for the plant and this is a major concern for operators as NCG in the cycle reduces plant efficiency.

3.2.4 *CLEAG-like concept*

Description

Information presented in this section comes from the AATG company website[9] and from personal communication. The concept is referred to as CLEAG (CloZEd Loop Energy AG, name of the company that developed the technology) or as AAT-Geothermae (name of the company that developed CLEAG's first power plant in Draškovec since 2013, in Croatia). The project was first awarded €14.7 M by the European Commission through a funding program for innovative low carbon energy technology (NER 300) in 2014. In 2020, the project was awarded €4.5 M by the European Commission through the Small-Scale Innovation Fund programme.

This concept consists of using the full energy potential of hot brines relying on both their temperature and their dissolved gases content. It targets geothermal fluids containing methane. In contrast to conventional geothermal power plants, CLEAG's hybrid system uses two sources for its energy production:

- Hot geothermal fluid (parameter estimates given by the demonstrator: reservoir temperature 100-120°C, depth 1800-2000 m) 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.
- Methane naturally dissolved in the geothermal fluid: methane is separated from the water and burned in a gas engine coupled to an alternator for the generation of electricity and heat in a combined heat and power (CHP) system.

In order to improve the environmental performance of exploitation:

- CO_2 naturally present in the produced geothermal well is also collected;
- The CO_2 from the exhaust gases of the gas engines is captured at a rate of 99.95% using an amine scrubber system.
- CO_2 from both origins is then co-injected with the cooled brine (out of the heat exchanger) in the geothermal reservoir at depth where it will be permanently stored in a dissolved form. This serves two purposes: primarily the CO_2 is sequestered underground and thus does not contribute to atmospheric CO_2 levels and, secondly, its reinjection balances the pressure in the reservoir.

The CLEAG technology uses these processes in a unique and patented way to create what is effectively a closed-loop hydrothermal geothermal power plant, combined with a near-zero-emission natural-gas-fuelled thermal power plant. The demonstration project comprises 4 production wells and 4 injection wells. The geothermal fluid extraction rate is around 80 kg/s/well, i.e. 320 kg/s for the 4 wells. Keeping a relatively high brine/CO_2 ratio (to guarantee full CO_2 dissolution) enables a CO_2 injection rate of 12.5 kt/yr/well, i.e. 50 kt/yr for the 4 wells.

[9] http://aatg.energy/, consulted August 2022

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, especially of the CO_2 capture unit, results in a net generation of 12 MWe).
The Draškovec geological formation is particularly suited for the CLEAG technology. It presents a reliable aquifer temperature of around 100°C at a depth of around 1900 m; numerous data and wells are available (5000 research wells in Croatia); the water under the Draškovec site is rich in natural gas. The methane content in the geothermal fluid is around 0.2% by weight.

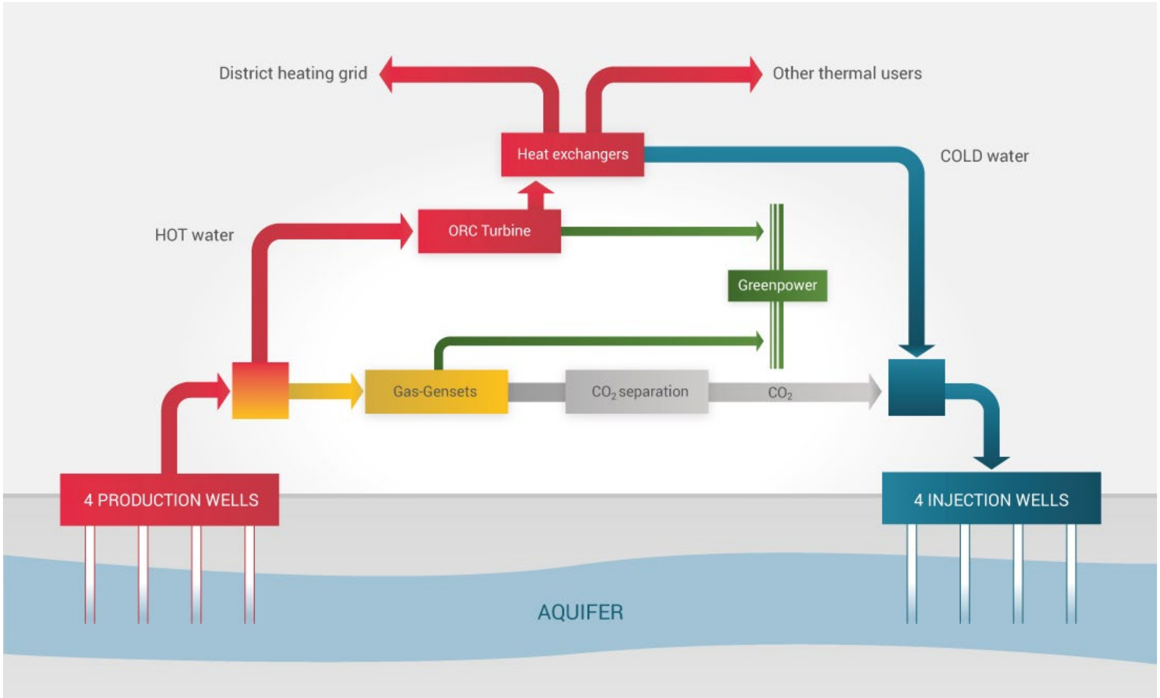


Figure 31. Illustration of the CLEAG concept. (http://aatg.energy/)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept requires specific geological features, notably a significant dissolved methane content in a permeable porous and permeable aquifer formation. For the demonstrator in operation, the targeted formations consist of sandstone (2 production wells) and limestone (2 production wells).	
	Porosity Permeability	Not found Around [10^{-14}-10^{-13}] m²
Depth	Range [1.8-2] km	
Dimensions	Thickness Extension	~200 m Kilometre scale
Temperature	[100-120] °C	
ENGINEERING		
Wells	4 production wells and 4 reinjection wells. Well design requirements: deviated wells, suitable for dissolved CO_2, for moderate temperature (100-120°C)	

Surface installations	Fluid pre-processing facilities (separator, scrubber, etc.) Heat exchanger and ORC turbine Gas turbine and capture facilities Facilities for injection in dissolved phase
Geothermal fluid	Flux of geothermal brine around 320 kg/s. Content in NCG: - CH_4:, ~0.64 kg/s (around 0.2% by mass) - CO_2: ~0.02 kg/s (around 0.006% by mass) NCG content for reinjection in geothermal brine (320 kg/s): - Methane combustion produces 1.76 kg/s of CO_2 (molar mass 16 g/mol for CH_4 and 44 g/mol for CO_2) - CO_2 captured in the extracted fluid: ~0.02 kg/s (around 0.006% by mass) The CO_2 reinjection rate is thus around 1.8 kg/s (around 0.6% by mass), reinjected in the dissolved form.
INTEGRATION	
Upstream	No CO_2 requirements from external source.
Downstream	Requirements: • Electricity production: connection to suitable voltage grid • Local valorization of co-produced heat
SERVICES PROVIDED	
Net baseload electricity production	Electricity production: around 20 MWe and 80 MWth. Around 8 MWe are used for internal processes, the net production is thus around 12 MWe.
CO_2 geological storage	The order of magnitude of avoided CO_2 emissions* is around 56 kt/y, i.e. 1.7 Mt over 30 years. * by comparison with a geothermal power plant exploited with current practice, with methane combustion and gases released to the atmosphere.
FROM CONCEPT TO MARKET	
Readiness	First pilot tests initiated in 2014 at Draškovec in Croatia. Industrial energy production delivered since 2017. A patent, no scientific articles.
Proponents and intellectual property	This technology has been patented by CLEAG and is deployed by AATG. The project was awarded €14.7 M by the European Commission in 2014 through a funding programme for innovative low carbon energy technology (NER 300), and €4.5 M by the Small-scale Innovation fund programme.
Availability of economic consideration	According to the website, the technology has a low LCOE and is already commercially self-sustaining.

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

Given the high heating value of CH_4 when compared to hot water, the concept could be seen as halfway between EGR and geothermal energy production. The replicability potential is estimated as being relatively high by the AATG team. However, for confidentiality reasons, the results of their study cannot be made available. One can think however that the need for high-CH_4 content of the brine is a significant limiting factor for a worldwide deployment of this technology whose primary objective clearly remains energy production and not CCS. The fact that CO_2 emissions to the atmosphere from CH_4 combustion are avoided is very positive.

3.2.5 *CO_2-DISSOLVED-like concept*

Description

This concept entails exploitation of a conventional geothermal doublet in a hydrothermal aquifer with brine as a fluid vector, with simultaneous CO_2 storage in the form of CO_2 dissolved in the reinjected brine (Kervévan et al., 2014; Randi et al., 2014; Kervévan et al., 2017; Randi, 2021). Due to the solubility limit of CO_2 in brine, it is adapted to small CO_2 industrial emitters (ca. <150,000 t/year). Contrary to CPG, CO_2 is injected and stored in entirely dissolved form in the saline aquifer. Water is pumped from a deep reservoir via a production well before being reinjected underground via an injection well (the two wells constituting a geothermal doublet), after dissolution of CO_2 captured at a nearby industrial plant. In most cases, the geothermal doublet will need to be installed close to the industrial emitter, but if there's an existing geothermal doublet located in the vicinity of the emitter, this could be reused in specific cases. Any CO_2 capture technology is compatible with CO_2-DISSOLVED but most of the published studies rely on the aqueous-based Pi-CO_2 capture technology (O'Neil, 2019), which is particularly well adapted to CO_2-DISSOLVED as it can directly provide carbonated water (that can be reinjected in the reservoir) rather than a CO_2 gas phase (that has to be dissolved in the injection well). Depending on the doublet geometry (distance between wells at depth) and operational conditions (water and CO_2 flow rates), the dissolved CO_2 plume will inevitably reach the production well at about 2-15 years after continuous injection started. Because the geothermal loop is a closed loop, CO_2 will not be released to the atmosphere but will be added to the reinjected brine-CO_2 flux, thus having to be accounted for so that the total reinjected CO_2 remains at a concentration below the solubility limit. In some cases (typically when injection rate is at saturation from the beginning of the injection period), this will result in a decreasing CO_2 injection capacity that operators should be aware of. A solution to this potential issue is either to increase the distance between wells (e.g. moving apart the well heads of a few hundred metres when possible), and/or adding a second geothermal doublet.

The temperature target of the geothermal resource, in the range of 60-80°C, aims at producing heat and not electricity, assuming that the recovered energy can be exploited locally in industrial processing, district heating, etc.

According to the authors (Kervévan et al., 2017), compared to the use of supercritical CO_2, this approach offers substantial benefits in terms of storage safety, due to lower brine displacement and no risk of pressure build-up in the aquifer, lower or no CO_2 leakage risk, and the potential for more rapid mineralization.

This concept was initially proposed by BRGM who coordinates the technology development in collaboration with several academic and industrial partners. Ongoing work is aimed at preparing the first CO_2 injection tests in an existing geothermal doublet, as a preliminary phase before proceeding with the first demonstrator of the full chain (capture, injection, storage, geothermal heat production) at an industrial site.

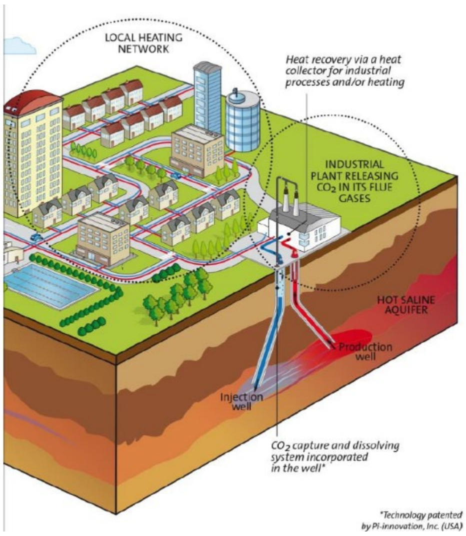


Figure 32. Illustration of the CO_2-DISSOLVED concept (Kervévan et al., 2014)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs a permeable aquifer formation in sedimentary basins.	
	Porosity Permeability	[15-25] % Around 10^{-14} m²
Depth	[0.8-2] km.	
Dimensions	Thickness Extension	[50-200] m Kilometre scale - Lateral extension [1-5] km
Temperature	[40-80] °C	
ENGINEERING		
Wells	A doublet Well design requirements: Generally deviated wells, suitable for dissolved CO_2, suitable for moderate temperature (below 100°C) Typical inter-well distance at depth: around 1,500 m	
Surface installations	Heat exchanger Facilities for CO_2 injection either as a gas phase (with “bubbler” implemented in the injection well) or already in dissolved phase (if Pi-CO_2 is used for capture).	
Geothermal fluid	Flux of geothermal brine around 50-100 kg/s Flux of CO_2 in injection well: around 1-5 kg/s, injected in the dissolved/gas form (depending on the capture technology used)	
INTEGRATION		
Upstream	CO_2 requirements from external source: around 1-5 kg/s	
Downstream	Requirements: • Local valorization of co-produced heat (heat or cold for industrial use, district heating network)	
SERVICES PROVIDED		
Net baseload electricity production	Heat production: The magnitude of heat production for a doublet in the Dogger formation is around 4-10 MWth.	
CO_2 geological storage	The CO_2 external inflow may have to decrease with time due to CO_2 breakthrough in the production well depending on operating	

	conditions (e.g. figure 7 in Kervévan et al., 2017). Considering in average a constant CO_2 flux of 40 kt/year, this yields to around 1.2 Mt of CO_2 stored over 30 years.
FROM CONCEPT TO MARKET	
Readiness	First published in 2014 Several scientific articles with modelling activities and technical developments for concrete concept validation, including mapping of possible sites. The first CO_2 injection test on an existing geothermal doublet is in preparation (no precise schedule available).
Proponents	This technology is proposed by BRGM and was developed through several academic-industrial partnerships led by BRGM.
Availability of economic consideration	Limited information. Unpublished work (confidentiality issues) achieved on a business model on an industrial case study (personal communication).

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

Given the relatively small quantity of CO_2 sequestered on a per well basis (a few tens of kilotons per year, typically), the CO_2–DISSOLVED concept will have relatively high investment and operational costs computed on a per mass of sequestered CO_2 basis. However, considering the evolution of the CO_2 price, the economic interest will certainly grow in the coming years, especially for small industrial emitters, scattered over territories, for which little to no solution is available to abate their CO_2 emissions. For those located in areas where a geothermal potential exists (first inventories made for France, Germany, USA, The Netherlands, showed a significant number of potentially favourable sites), CO_2-DISSOLVED could then be a well-adapted solution to decarbonizing these industrial sites, with additional economic and environmental benefit from geothermal heat production. A first demonstration pilot is clearly missing to better assess the technical feasibility and the global performance of this concept.

3.2.6 *Other variants*

In section 3.2.1, we present an overview of the different concepts that have moved to pilot (at least preparation) or demonstrator stage. These concepts have been detailed.

Considering the characteristics provided in Table 9, other variations of concepts can be imagined, with different combinations of features, depending on the:

- Geothermal fluid content:
  - Brine only, brine and CO_2, brine and CH_4 (and CO_2).
  - Percentage of gases
  - Main fluid phase (liquid, vapour, two-phase)
- Reservoir characteristics:
  - Permeable aquifer formation, with tight caprock (where gaseous/supercritical CO_2 can be contained by structural trapping), permeable aquifer formation (where CO_2 can be contained by solubility trapping), reactive mafic or ultramafic rock (with short-term mineral trapping opportunity)
  - Porous matrix, or porous matrix with fractures.
  - Depth

  - Temperature
- Surface opportunities:
  - Nearby CO_2 emitter and opportunity of CO_2 storage from this local source;
  - Emitter with CO_2 capture, geothermal energy requirements for capture processes;
  - Opportunity for heat utilization (industrial use, DHN).
  - Possibility to connect to suitable voltage grid for electricity production.
- Targeted ratio for CO_2 flux compared to brine flux, that conditions the possible injection forms:
  - Dissolved form possible up to a few percent (depending on pressure, temperature, salinity, etc.)
  - Liquid CO_2-brine co-injection (containment should be guaranteed)
  - Supercritical CO_2 (containment should be guaranteed)
- Operation size: for a doublet, co-injection of CO_2 and brine is required. For a larger number of wells, different layouts can be tested. A well can be dedicated to pure CO_2 reinjection for example.

3.2.6.1 Geothermal-BECCS concept

Bio-CCS or BECCS (BioEnergy with Carbon Capture and Storage) is defined as "processes in which CO_2 originating from biomass is captured and stored. These can be energy production processes or any other industrial processes with CO_2-rich process streams originating from biomass feedstocks. The CO_2 is separated from these processes with technologies generally associated with CCS for fossil fuels. Biomass binds carbon from the atmosphere as it grows; but with the conversion of the biomass, this carbon is again released as CO_2. If, instead, it is captured, transported to a storage site and permanently stored deep underground, this would result in a net removal of CO_2 from the atmosphere" (Kemper, 2015).
In its original form, there is no hybridization with geothermal energy (cf. Figure 33).

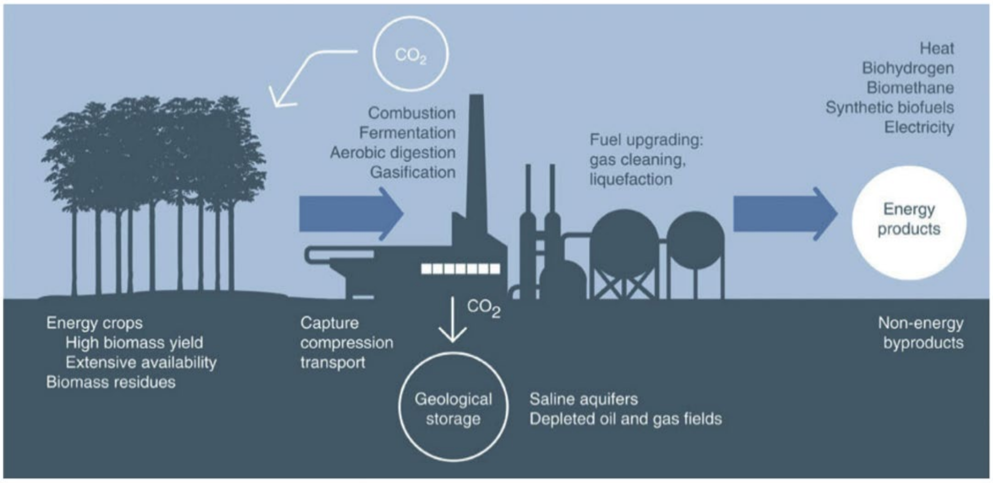


Figure 33. Illustration of the BECCS concept (Kemper, 2015)

A recent concept proposed by Titus et al. (2022) introduces possible hybridization with geothermal energy in order to improve further the environmental and energy performance of the system, as illustrated in Figure 34. The concept is close to the CO_2-DISSOLVED one (which may be implemented on a biomass plant as well), but presents some differences:

- There is a requirement on the nature of the source of CO_2 that is stored (from biomass energy);
- The geothermal heat is used in synergy with biomass energy to boost power production (different possible layouts), generally targeting electricity production.

- It targets larger power plants (around 100 MWe) and higher CO_2 storage volumes (0.25-0.63 Mt/year).

As highlighted by the authors, "this dual approach of using geothermal systems for power production and as carbon sinks has the potential to decarbonize energy systems in areas with suitable geothermal and bioenergy resources". The negative emissions intensity of the whole system is between -200 and -700 g CO_2/kWh.

Five configurations were tested: flash, total flow, ORC binary, compound flash-binary, and distilled water binary plant design.

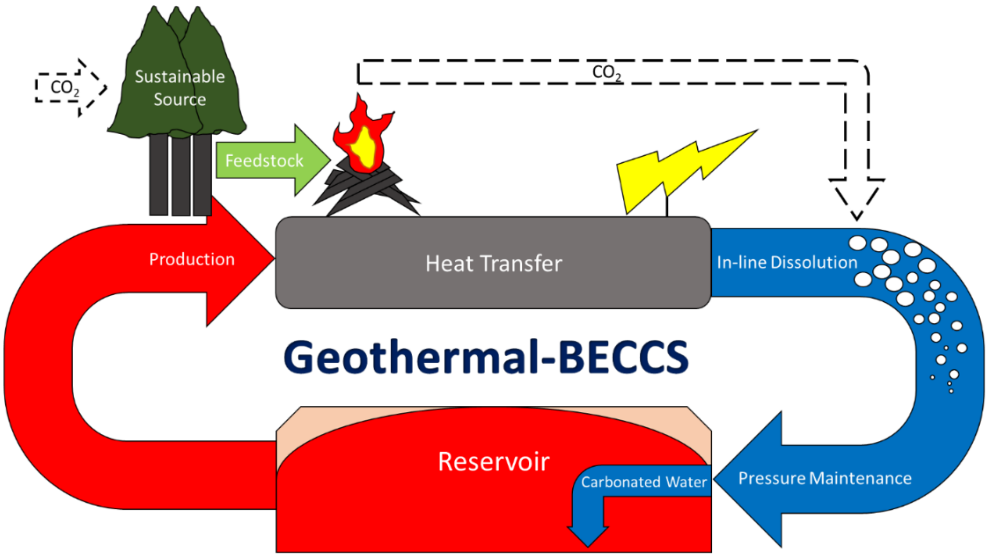


Figure 34. Illustration of the Geothermal-BECCS concept (Titus et al., 2022)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

	UNDERGROUND CHARACTERISTICS	
Geology and petrophysical properties	In Titus et al., 2022, the geological features are briefly described and some elements are inspired from the CarbFix Icelandic context (with limited depth and 160°C temperature). However, it seems reasonable to consider wider replicability of the concept in more common contexts, for instance in deeper permeable aquifer formations in sedimentary basins.	
	Porosity	NA
	Permeability	NA
Depth	0.5-3 km (fuzzy information at the moment)	
Dimensions	Thickness	NA
	Extension	NA
Temperature	Around 160°C	
	ENGINEERING	
Wells	Several doublets to reach the mentioned brine flow rate. Well design requirements: Generally vertical wells, suitable for dissolved CO_2, suitable for moderate temperature around 160°C	
Surface installations	Heat exchanger and ORC turbine, or direct steam turbine Biomass boiler and heat exchanger Facilities for injection in dissolved phase	
Geothermal fluid	Flux of geothermal brine around 400-1200 kg/s	

	Flux of CO_2 in injection well: around 7-20 kg/s, injected in the dissolved form (1.6% by mass)
INTEGRATION	
Upstream	Biomass requirements for the biomass heater: between 25 and 71 kg/s
Downstream	Requirements: • Electricity production: connection to suitable voltage grid
SERVICES PROVIDED	
Net baseload energy production	Electricity production: The order of magnitude for electricity production is 100 MWe (from geothermal and biomass energies). This power plant size is scalable. For sake of comparison, we consider only the percentage of energy provided by geothermal energy. It is not detailed in the article, but it is probably in the range 20-50%. It can thus be considered that the electricity production attributed to geothermal energy is around 20-50 MWe.
CO_2 geological storage	Range: 7-19 Mt over 30 years. Since the scope considered here is the hybridization between geothermal power plant and CCS (excluding biomass power plant), it is considered that CO_2 is stored from an external emitter.
FROM CONCEPT TO MARKET	
Readiness	First published in 2022
Proponents	Published by University of Canterbury (New Zealand)
Availability of economic consideration	Limited information

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

At first glance, this concept seems very similar to CO_2-DISSOLVED. However, geothermal BECCS is more complex to set up as it i) targets deeper reservoir at higher temperature (*ca.* 160°C) to produce electricity, ii) needs several doublets to reach the expected dissolved CO_2 flow rates (*ca*. 200-600 kt CO_2/yr), and iii) needs availability of a large biomass plant emitting sufficiently high CO_2 rates. All these requirements certainly have an impact on the actual replicability potential. It has to be noted that CO_2-DISSOLVED is fully compatible with BECCS, provided that the industrial site is burning biomass and emits CO_2 at relatively moderate rates (*ca*.10-100 kt CO_2/yr); it could then be an alternative to this concept for biomass plants with compatible emission rates.

3.2.6.2 CCS-driven concept (geothermal energy used for capture and for storage in the dissolved form)

This concept, presented in a scientific article by Ganjdanesh et al. (2013), is illustrated in Figure 35.

The concept has similarities with CO_2-DISSOLVED: it consists of injecting CO_2 from an external emitter and in dissolved form using the reinjection well of a geothermal doublet, and using the brine for energy production. The main differences are the following:

- The philosophy that leads the concept is: "starting from CCS capture facilities, and considering the necessity of underground drilling, would it be 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, and not by geothermal heat extraction.
- Thus, the sizing of the concept is designed to fulfil the CCS facility needs: considering the CO_2 captured flux (116 kg/s), the geothermal fluid flow (~2200 kg/s)

corresponds to the flux required for reinjection of all the CO_2 in dissolved form, considering the solubility limit (5.4% by weight). The required number of wells (15 injectors and 15 producers) is then deduced.

- As with the CLEAG concept, the geothermal fluid is assumed to contain methane with concentrations on the order 0.4% by weight (30-45 standard cubic feet per barrel). This leads to a methane production of around 8 kg/s, which produces around 250 MWe. In addition, the geothermal heat produces around 500 MWth.

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

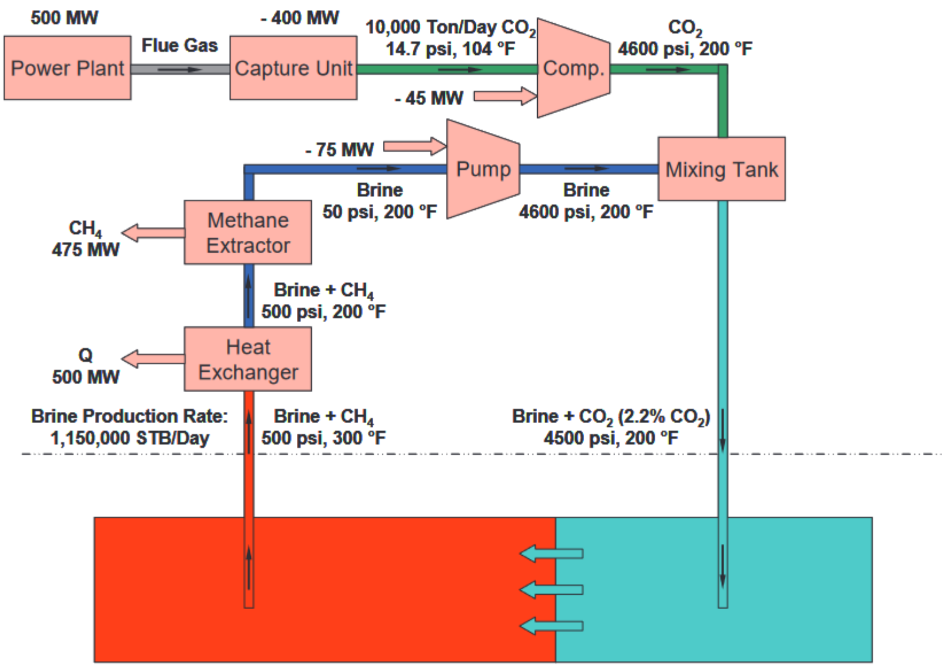


Figure 35. Illustration of the CCS-driven concept (Ganjdanesh et al., 2013)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept was investigated for a geopressured-geothermal aquifer with high dissolved methane content (0.4% by weight).	
	Porosity Permeability	Around 20% Around [10^{-14} ; 10^{-13}] m²
Depth	Around 3 km	
Dimensions	Thickness Extension	~100 m Kilometre scale
Temperature	Around 150°C	
ENGINEERING		
Wells	Simulations used parallel well patterns. The number of wells required to fulfil the CCS plants requirements is 15 injectors and 15 producers.	
Surface installations	Fluid pre-processing facilities (separator, scrubber, etc.) Steam turbine or heat exchanger and ORC turbine	

	Gas turbine and capture facilities Facilities for injection in dissolved phase
Geothermal fluid	Flux of geothermal brine around 2200 kg/s. Content in NCG: CH_4: ~8 kg/s (around 0.4% by mass) Reinjection with CO_2 from external power plant: brine around 2200 kg/s and CO_2 content 120 kg/s (around 5.4% by mass)
INTEGRATION	
Upstream	CO_2 from external source: around 120 kg/s
Downstream	Requirements: • Energy production: main use for capture processes. • Valorization of excess heat / electricity
SERVICES PROVIDED	
Net baseload energy production	Methane turbine produces between 142 and 285 MWe. In addition, the geothermal brine produces around 500 MWth.
CO_2 **geological storage**	Around 120 Mt over 30 years.
FROM CONCEPT TO MARKET	
Readiness	One scientific article. In 2013
Proponents	University of Texas (USA)
Availability of economic consideration	Limited information. According to authors, "preliminary calculations indicate that the revenue from the energy in hot brine saturated with methane can offset much of the costs of CCS".

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

There is limited information and debate on the feasibility of this concept. Moreover, the following points should be further addressed in order to strengthen the concept:

- the CO_2 will probably reach the production well after some years; it can be reinjected, but it will limit the quantity of additional external CO_2 that can be dissolved;
- the methane content might decrease over time;
- the volumes (water, reservoir) required for such huge quantities of CO_2 in dissolved form are high (a reason for CO_2 storage in the supercritical form is related to the much higher supercritical density). This raises some questions regarding feasibility.

By comparison with scenarios proposed in Buscheck and Upadhye (2021), where geothermal energy is used to pre-heat the boiler feedwater, it seems that using geothermal energy for capture does not optimize the overall energy efficiency. Concepts presented in section 3.3.3 might be more promising to optimize synergy between fossil-fuel power plant, geothermal energy exploitation and CO_2 storage.

3.3 Other surface/underground synergetic uses

Sections 3.1 and 3.2 present the strong hybridization between heat mining and CO_2 management (the geothermal fluid is CO_2 or the geothermal fluid contains CO_2). In the present section, other synergetic uses between CCS and heat mining are presented with the use of:

- Pressure management to improve the performance of both CCS and geothermal heat extraction. Brine is not necessarily reinjected in the same formation (section 3.3.1, underground synergetic use)
- The same reservoir for both uses, at some distance (~7 km), with mutualization of the injection well for both CO_2 injection and brine reinjection, sharing of the exploration phase and the data (section 3.3.2, underground synergetic use)
- Heat mining as an energy source in synergy with other energy sources, in a system that includes CO_2 capture and storage (section 3.3.3, surface and underground synergetic use)
- Heat mining as an energy source for CO_2 capture. The published information focus on the geothermal component, and the underground relative locations of both uses is not addressed (section 3.3.4, surface synergetic use)

3.3.1 *Synergetic use through pressure management*

For underground exploitations, different characteristic volumes can be defined, in particular: the volume encompassing the zone concerned by fluid circulation, thermal perturbation, and pressure variation.

In terms of pressure, for CCS, CO_2 injection provokes a pressure increase in the reservoir. It limits injectivity and storage capacity and increases seismic and leakage risks. Therefore, pressure decrease through water withdrawal in the vicinity could improve capacity and limit the risks, assuming these retrieved volumes of brine can be managed at the surface.
Solutions of Active CO_2 Reservoir Management (ACRM) have been proposed by different authors to improve CCS performance. They consist of withdrawing water from the storage reservoir.
The concept was first proposed by Bergmo et al. (2011) and Buscheck et al. (2011). Buscheck et al. (2011) detailed the main expected benefits as:

- reduction of pressure buildup (in magnitude, areal extent, and duration) and associated failure risks, leading to increased storage capacity and a significantly smaller area of review and seismic risk;
- “push-pull” manipulation of the CO_2 plume, reducing CO_2 contact with the caprock seal and increasing the fraction of the storage formation used for trapping mechanisms;
- additional valuable information to speed upstorage-system calibration and history-matching;
- decoupling of neighbouring CO_2 operations from each other, with respect to pressure interference, which allows planning, assessing, and conducting of each operation to be carried out independently; as a consequence, reduction of costs, increase of performance and gain of public acceptance.

Buscheck et al. (2016) also showed that pre-injection brine production can be a useful way to assess the CO_2 storage capacity of a reservoir prior to injecting CO_2.

In order to make pressure decrease in the reservoir effective, a volume of brine equivalent to the volume of injected CO_2 should be produced (Bandilla and Celia, 2017). The water should not be reinjected directly at a close location in the same reservoir. Different outlets can be proposed for the extracted water; it can be:

- desalinated in order to produce drinking water (Bergmo et al., 2011; Buscheck et al., 2011);
- released into the ocean (after suitable treatment) (Bergmo et al., 2011);
- reinjected into the same reservoir at some distance (Buscheck et al., 2013);
- reinjected into a shallower or deeper reservoir (Buscheck et al., 2013; Buscheck and Upadhye, 2021).

The extracted water, before being reinjected, can be used for geothermal heat/electricity production. In the present section, we focus on these options that operate hybridization between CCS and geothermal heat extraction. This solution is proposed in a limited number of articles.

It should be noted that the synergetic use of a reservoir for geothermal energy exploitation and CO_2 storage through pressure management will not only improve the CCS performance but also the geothermal heat mining: for heat mining, there is generally a depressurization close to the production well. Pumping is required in the production well in order to extract fluid. Thus, pressure increase in the reservoir due to CO_2 injection, including the production well area, could lead to energy saving.

A first configuration inspired from a realistic geological site is proposed in Nielsen et al. (2013). CO_2 injection takes place in 2 central injection wells, and brine production for geothermal heat extraction takes place in 4 surroundings locations, as illustrated in Figure 36 (the location is fixed by the actual location of four cities). Simulation cases with different volumes of water reinjection are compared. Handling the water that is not reinjected should be considered (not addressed).

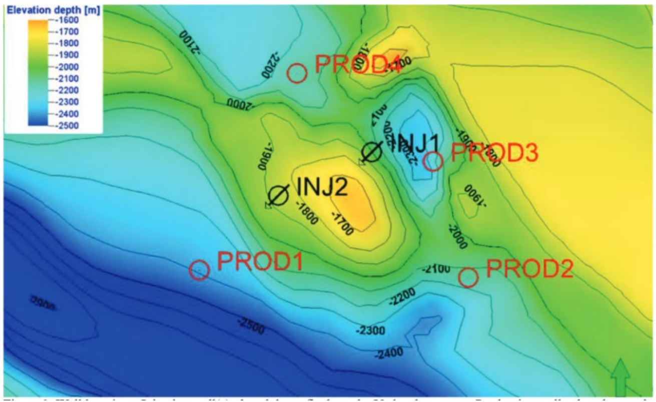


Figure 36. Illustration of the configuration proposed for synergy benefits (Nielsen et al., 2013)

Another configuration is presented in Buscheck et al. (2013). The philosophy in this case is to manage pressure. In most cases, the produced fluid consists of brine only. Different configurations with concentric rings were tested: (1) inner brine/CO_2 producers, (2) CO_2 injectors, (3) brine injectors, and (4) outer brine producers. These rings are used to create a hydraulic ridge and cap to suppress CO_2 migration and leakage. In addition to managing overpressure, the authors show that the concept can produce geothermal energy and water to significantly defray the parasitic costs of CO_2 capture. It should be noted that in some cases the layout leads to co-production of brine and CO_2 after some time (see Figure 37), thus the system becomes close to the ones presented in section 3.1.1.

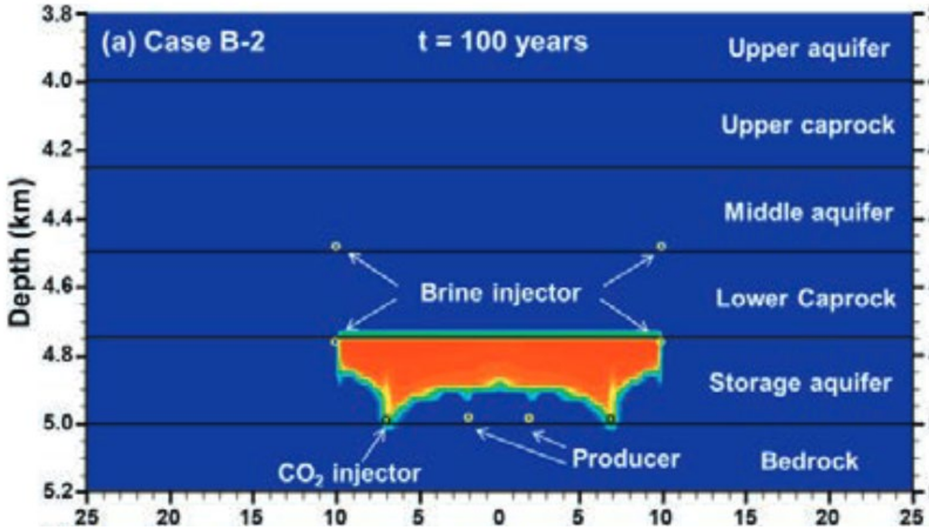


Figure 37. Illustration of integrated geothermal-CO_2 reservoir systems (Buscheck et al., 2013).

Table 10. Synergetic use through pressure management or same formation use

References	Buscheck et al., 2013	Nielsen et al., 2013	Buscheck and Upadhye, 2021	Tillner et al., 2013
Country	/	Denmark	/	Germany
Synergy	Pressure management			Same formation (infrastructure and data sharing)
Geology	Sedimentary aquifer Permeability 10^{-13} m²	Porous and permeable sandstone	Sedimentary aquifer	Porosity 23% and permeability 4 x 10^{-13} m²
Layout	Radial configuration (CO_2 injection at center, radial brine extraction)	2 CO_2 injectors. 4 geothermal doublets (with partial reinjection)	9 CO_2 injectors and 4 brine production wells for geothermal brine production and pressure reservoir management	1 CO_2 injector, 1 brine producer
Depth	2500 m (or 5000 m)	Between 1000 and 3000 m	Around 2000 m	1080 m
Initial temperature	100°C (or 260°C)	Not mentioned	90°C	50°C
CO_2 flux	480 kg/s	100 kg/s		54 kg/s
Localization brine producer	Centre and/or periphery (distance ~5 km)	In a radius up to 10 km from the CCS storage		7 km from the CO_2-brine injector
Localization brine injector	3-6 km (at periphery) from CO_2 injector and/or shallower aquifer	Partial reinjection.		Brine is injected with CO_2, with cycles.
Brine flux	Up to same flow volume.	46 kg/s		20 kg/s
Heat/power capacity	200-500 MWth	Not mentioned		Not mentioned

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs a porous and permeable aquifer formation suitable for both geothermal energy extraction and CCS, overlain by an impermeable caprock for carbon storage.	
	Porosity	NA
	Permeability	~10^{-13} m²
Depth	Around 1-3 km for geothermal exploitation	
Dimensions	Thickness	NA
	Extension	NA
Temperature	Around 50-150°C	

ENGINEERING	
Wells	Geothermal energy system: several production wells in the main reservoir. Different options for water disposal (at some distance, partial reinjection, release in seawater, injection in another aquifer) At least one injection well for CO_2 injection.
Surface installations	Facilities for CCS (carbon supply and injection) Facilities for heat mining (heat exchanger with heat uses or electricity production in a turbine).
Fluid flows	Brine flow ~50-250 kg/s CO_2 flow ~100-500 kg/s
INTEGRATION	
Upstream	CO_2 requirements from external source ~100-500 kg/s
Downstream	Requirements: • Electricity production: connection to suitable voltage grid or • Local valorization of produced heat
SERVICES PROVIDED	
Energy production	Order of magnitude: 50-500 MWth
CO_2 geological storage	Order of magnitude: 100-500 Mt over 30 years
FROM CONCEPT TO MARKET	
Readiness	First published in 2013. Limited number of scientific articles. A Danish realistic case study is presented. Since both technologies (geothermal energy exploitation and CO_2 storage) are used more or less independently and are mature, the TRL of this concept should be considered as relatively high.
Proponents	This technology is proposed by European and US researchers.
Availability of economic consideration	No information

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Until now, we convey the state of the art as presented in the literature, without introducing a subjective view. Here we also introduce some additional subjective opinions expressed by the authors and reviewers where relevant.

At first sight, this approach is interesting as it greatly improves the management of CO_2 injection into the aquifer by controlling the pressure. However, although the proposed solution works in theory, its practical applicability needs to be further discussed, as the water extracted from the aquifer needs to be managed once the calories it contains have been recovered. The quality of the water (particularly the salinity, which is likely to be relatively high in deep aquifers) is critical to what can be done without harming the environment if the water is disposed of in seawater (assuming the site is at a reasonable distance from the sea) or a nearby river (if flow rates make it feasible). Reinjection into other aquifers should eventually lead to a pressure build-up problem in these aquifers, so we don't think it is a viable long-term option. Desalination may be interesting in some cases, but it is an energy-intensive technology and the highly concentrated brines produced by the process need to be disposed of, which can be even more complex than for the original brine.

3.3.2 *Synergetic dual use in the same reservoir*

Description

Another possible synergy is to use the same reservoir for both geothermal heat mining and CCS. The exploration phase, data acquisition, and some infrastructures can thus be mutualized. This concept is proposed by Tillner et al. (2013) with a case study in Germany as illustration. 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 CO_2 injection and brine reinjection (with cycles), with a mutualization of drillings.
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. The projects characteristics are summarized in Table 10.

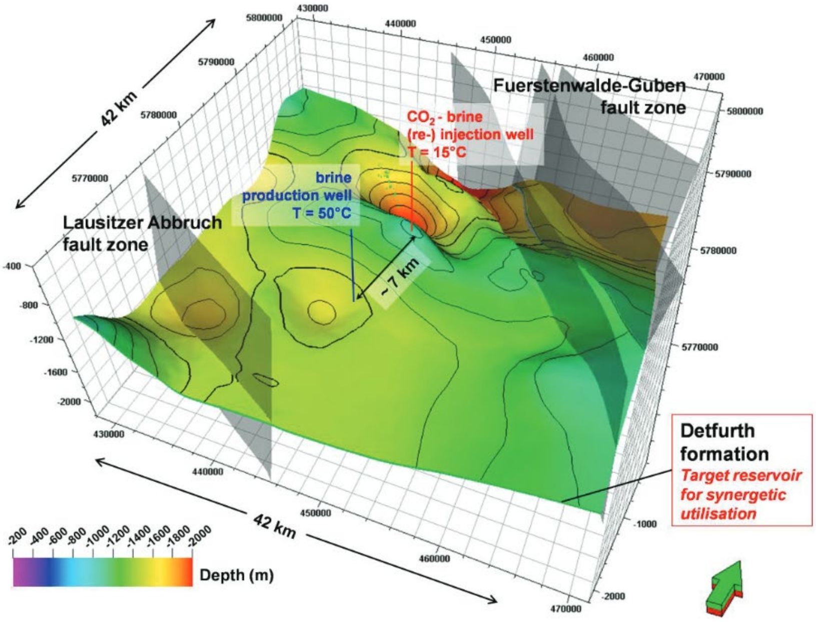


Figure 38. Illustration of the synergetic utilization proposed in Tillner et al. (2013)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs a porous and permeable aquifer formation suitable for both geothermal energy extraction and CCS, overlain by an impermeable caprock for CO_2 storage.	
	Porosity Permeability	~20% ~10^{-13} m²
Depth	Around 1 km	
Dimensions	Thickness Extension	NA NA
Temperature	Around 50°C	
ENGINEERING		
Wells	At least one brine production well At least one injection well for CO_2 injection and water reinjection	
Surface installations	Facilities for CCS (carbon supply and injection)	

	Facilities for heat mining (heat exchanger with heat uses or electricity production in a turbine).
Geothermal fluid	Brine flow ~20 kg/s CO_2 flow ~50 kg/s
INTEGRATION	
Upstream	CO_2 requirements from external source ~50 kg/s
Downstream	Requirements: Local valorization of produced heat
SERVICES PROVIDED	
Energy production	Not mentioned
CO_2 geological storage	Order of magnitude: 50 Mt over 30 years
FROM CONCEPT TO MARKET	
Readiness	Published in 2013. 1 article. A German realistic case study is presented. Since both technologies (geothermal energy exploitation and CO_2 storage) are used more or less independently and are mature, the TRL of this concept should be considered as relatively high.
Proponents	One German research team.
Availability of economic consideration	No information

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Here we convey the state of the art without introducing a subjective view. We also introduce additional subjective opinions expressed by the authors and reviewers.

The study presented in Tillner et al. (2013) is interesting as it presents results for a specific geological site for which data were available. Various scenarios were tested with different hypothesis on some key parameters. Although positive, the conclusions on the feasibility of this approach must not be extrapolated to other reservoirs. The modelling approach has to be kept as a methodological reference but no conclusion can be drawn on the replicability to other sites. Interestingly, the technologies used are well-known, making this approach potentially mature (or close to be) for setting up tests on a relatively short term, provided an appropriate reservoir can be found. Nevertheless, the pressure build-up issue in the reservoir, encountered in conventional supercritical CO_2 storage projects, still exists in this case as CO_2 is co-injected with the water previously retrieved from the reservoir at the production well.

3.3.3 *Hybrid energy systems involving both technologies*

Buscheck and Upadhye (2021) propose a hybrid-approach in order to produce electricity with near-zero carbon emissions (or even negative emissions if biomass is used) (cf. Figure 39). 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. For instance, 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 optimize the CCS process, CO_2 is produced with high purity, relying on combustion with pure oxygen (oxy-combustion), produced by an air separation unit that uses excess electricity or auto-produced electricity (depending on scenarios). CO_2 can be dehydrated and compressed for transport in a CO_2 pipeline and storage during periods of excess electricity.

The authors present different scenarios that propose to tackle the challenges of excess electricity use, energy storage, production of electricity on-demand.

Up to 35% of gross power can be derived from renewable sources, with a conversion rate of renewable energy to electricity above 40%. Such a power plant can also work with biomass instead of fossil energy. In this case, 100% of gross power is derived from renewable energy.

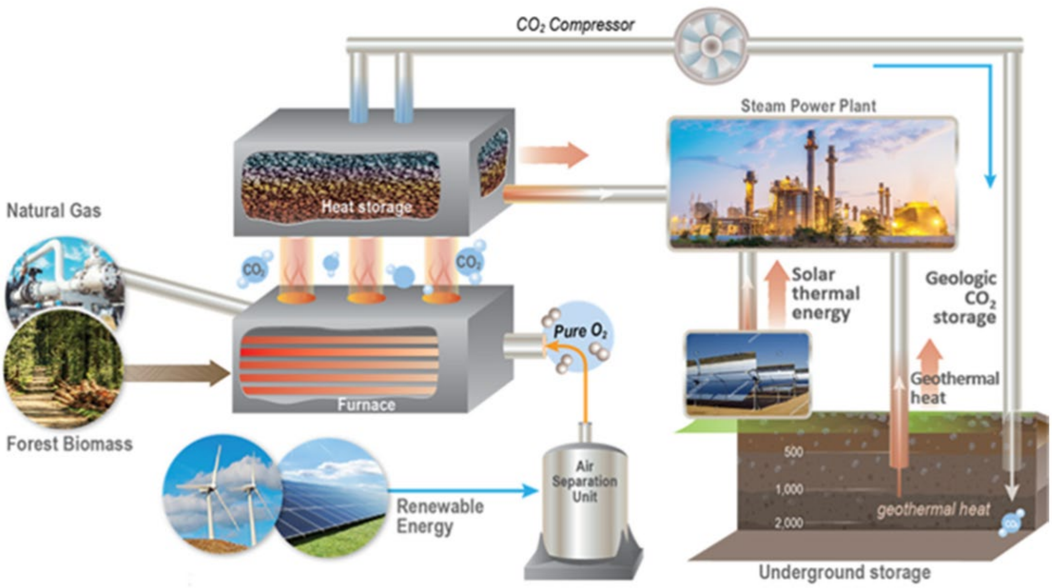


Figure 39. Hybrid-energy approach enabled by heat storage and oxy-combustion to generate electricity with near-zero or negative CO_2 emissions (Buscheck and Upadhye, 2021)

Concerning the underground set-up, a possibility is displayed in Figure 40. Geological CO_2 storage is deployed in a sedimentary formation, with supercritical CO_2. In order to manage pressure in the storage formations, brine is extracted at some distance, geothermal heat is used in the power plant, and a part of the geothermal brine might be reinjected in a shallower formation. The shallower formation is also used for thermal heat storage (e.g. variable solar heat). The heat from storage is re-produced on-demand in order to pre-heat the fluid.

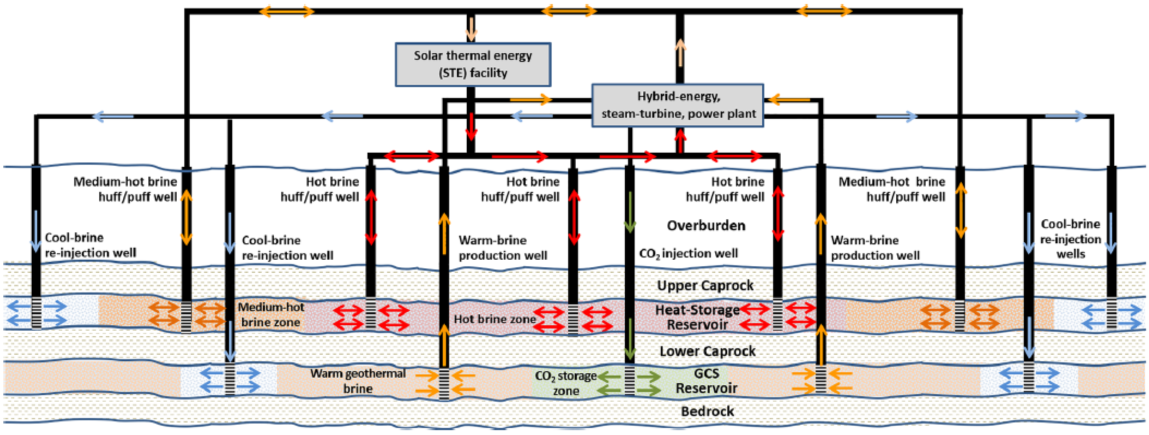


Figure 40. Underground part of the hybrid-energy approach (Buscheck and Upadhye, 2021)

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs: - A permeable aquifer formation in sedimentary basin overlain by an impermeable caprock for carbon storage - A shallower aquifer formation for heat storage	
	Porosity Permeability	NA NA
Depth	Around 1-2 km (examples provided in the article: 1.2 km for the shallower aquifer and 2 km for the CO_2 storage aquifer)	
Dimensions	Thickness	Examples provided in the article: 50 m for the shallower aquifer and 400 m for the CO_2 storage aquifer
	Extension	NA
Temperature	90°C for the geothermal fluid, up to 250°C for the artificial geothermal reservoir	
ENGINEERING		
Wells	CO_2 storage formation: 9 CO_2-injection wells and 4 brine production wells for geothermal brine production and pressure reservoir management. Underground Thermal Energy Storage: 36 wells (most of them are huff-puff wells)	
Surface installations	Industrial power plant (e.g. a 550 MW power plant) with air separation unit, furnace, heat storage in granular media, steam power plant, etc. Facilities for CCS (CO_2 injection)	
Geothermal fluid	The total geothermal brine flow rate is 271 kg/s in the case study.	
INTEGRATION		
Upstream	CO_2 is captured from the fossil/biomass power plant.	
Downstream	Geothermal energy is used in synergy with other energy resources to optimize performance.	
SERVICES PROVIDED		
Energy production	The dispatched power is 550 MWe. The contribution of geothermal energy is comprised between 21 and 75 MWe.	
Energy storage	The system offers services in terms of:	

	- excess electricity use, - short-term energy storage (notably is granular media in vessels), - seasonal energy storage, notably in underground thermal energy storage, - production of electricity on-demand.
CO_2 geological storage	An objective of the system is to store CO_2 from the power plant (550 MWe). The CO_2 flux is comprised between 1.9 and 3.8 Mt/year, i.e. between 57 and 114 Mt for 30 years of operations
FROM CONCEPT TO MARKET	
Readiness	First published in 2021. Only one scientific article. The TRL of this concept should be considered as low due to the complexity of the overall system.
Proponents and intellectual property	This technology is proposed by Lawrence Livermore National Laboratory and Upadhye ARU Associates. The technology is patented.
Availability of economic consideration	Limited information

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the Excel spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Here we convey the state of the art without introducing a subjective view. We also introduce additional subjective opinions expressed by the authors and reviewers.

Hybrid-energy systems are promising to optimize the energy performance. Theoretically, the concept is appealing, but the practical implementation requires dealing with numerous challenges (complex surface installations, high temperature underground energy storage, compliance with local CO_2 storage regulations, reinjection of brine in a different aquifer, two aquifers at a same location, very high number of wells, etc.). The TRL of the concept should thus be considered as low.

3.3.4 *Geothermal energy used for capture*

Description

This concept is described by Davidson et al. (2017). Contrary to most concepts described in this literature review, the main objective remains the storage of CO_2. When analysing the whole chain, the authors point out that the energy consumption of the CO_2 capture process is a non-negligible penalty for carbon reduction. (if the energy required for capture is supplied by a non-neutral carbon energy plant, the net carbon reduction is cut down by the associated supplementary carbon emissions). In order to improve the benefit of CO_2 storage, the authors investigated the potential to use geothermal energy to preheat the boiler feedwater. The theoretical results of this study indicate a promising performance of using geothermal energy (at 150°C) to increase the benefits of CCS with power load associated with a MEA (MonoEthanolAmine)-based capture technology that could be offset by roughly 7%.

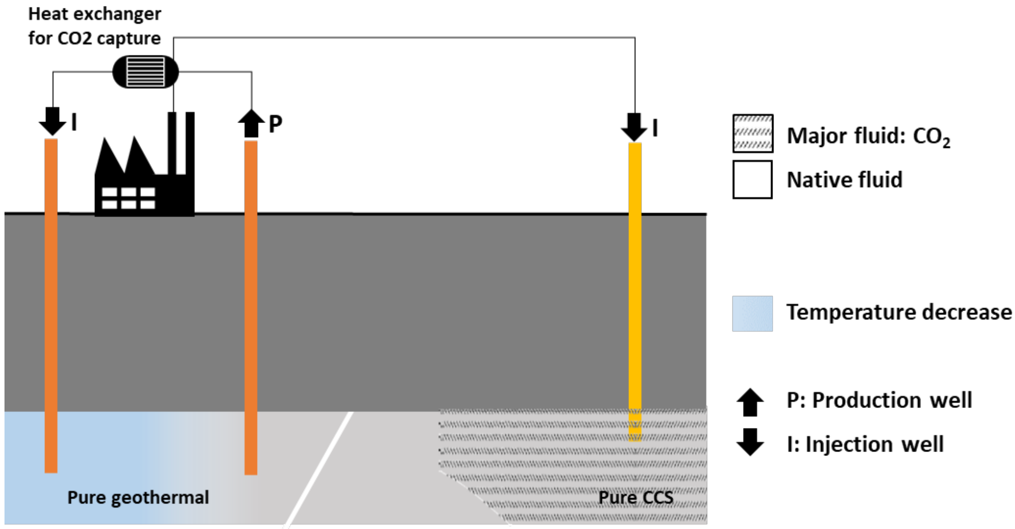


Figure 41. Illustration of the concept "Enabling CCS via low-temperature geothermal"

Another option proposed in the literature to use geothermal energy for capture consists of using geothermal energy in Direct Air Carbon Capture (Pilorgé et al., 2019; McQueen et al., 2020; Adams et al., 2020). This concept was not thoroughly investigated within the present study, but constitutes a promising option of synergy between geothermal energy and CCS, as illustrated by the Orca[10] project in Iceland. In this project, the Climeworks' DAC system has been operated since 2021 with associated CO_2 storage (4,000 t/yr) with the CarbFix solution. The heat and electricity required to run the direct air capture process is supplied by the Hellisheidi geothermal power plant.

Characteristics

Foreword: Figures presented here are indicative. It was chosen to present ranges of values corresponding to commonly used values and not to extreme values.

UNDERGROUND CHARACTERISTICS		
Geology and petrophysical properties	The concept needs: - A permeable aquifer formation for geothermal energy extraction - A permeable aquifer formation in sedimentary basin overlain by an impermeable caprock for carbon storage (not described in the article)	
	Porosity	NA
	Permeability	NA
Depth	Around 1.5-2 km for geothermal exploitation	
Dimensions	Thickness	NA
	Extension	NA
Temperature	Around 150°C	
ENGINEERING		
Wells	Geothermal energy system: 4 or 5 injection wells, 3 production wells At least one injection well for CO_2 injection (not described in the article).	
Surface installations	Industrial power plant, e.g. a 550 MW pulverized coal-fired power plant. With MEA (monoethanolamine) capture system or CO2BOLs (CO_2-binding organic liquids) capture system.	

[10] https://climeworks.com/roadmap/orca

	Or Direct Air Capture facilities Heat exchanger to convey geothermal heat to capture process. Facilities for CCS (CO_2 injection)
Geothermal fluid	The total geothermal brine flow rate is around 2 500 000 lb/h, which corresponds to ~ 314 kg/s for the 4-5 injection wells. If we consider emissions around 1 kg CO_2/kWh, the CO_2 flux can be estimated around 150 kg/s (order of magnitude, not provided in the article).
INTEGRATION	
Upstream	CO_2 is captured from a power plant (e.g. coal-fired power plant).
Downstream	Geothermal energy is used for the capture process.
SERVICES PROVIDED	
Energy production	There is no electricity production directly from geothermal energy extraction. However, using geothermal energy for carbon capture allows an increase of efficiency, with +10 MWe for the 550 MWe power plant.
CO_2 geological storage	The primary objective of the system is to store CO_2 from a coal-fired power plant (550 MWe). If we consider emissions around 1 kg CO_2/kWh, the 550 MWe power plant produces around 5 Mt/year, i.e. around 150 Mt for 30 years of operations (this should only be considered as an order of magnitude, not provided in the article)
FROM CONCEPT TO MARKET	
Readiness	First published in 2017. Only one scientific article, focusing mainly on the surface process (modelling with ASPEN). The scientific article proposes a realistic case study for the North Valmy power plant (USA). Since both technologies (geothermal energy exploitation and CO_2 storage) are used independently and are each mature, the TRL of this concept should be considered as high.
Proponents	This technology is proposed by an academic team in the US (Pacific Northwest National Laboratory).
Availability of economic consideration	LCOE: increase capacity by 10 MW at an incremental cost of electricity between \$0.06 and \$0.07/kWh

Advantages, Drawbacks and challenges

The reader is referred to the detailed summary of all concepts delivered in the spreadsheet file and reported in the Appendix.

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

Critical considerations

Foreword: Here we convey the state of the art without introducing a subjective view. We also introduce additional subjective opinions expressed by the authors and reviewers.

The present concept was integrated in the study because geothermal energy is used directly for CO_2 capture, but concepts presented in section 3.3.3 might be more promising to optimize synergy between fossil-fuel power plant, geothermal energy exploitation and CO_2 storage.

3.4 Borderline concepts

The concepts in this section are considered borderline and out of the scope of the present study. Nonetheless, being close to the perimeter of the study, the concepts deserve a few words to clarify their position, and to justify why they were not considered within the present study.

3.4.1 *CCES (Compressed CO_2 Energy Storage)*

Foreword: This technology is not included in the present review since it does not rely on geothermal exploitation. However, it is very much borderline. Storage round trip efficiency over 100% indeed denotes thermal contribution of the underground.

As introduced in section 2.3, several renewable energies exhibit intermittence and fluctuation, which is a hurdle for grid stability and for balance between supply and demand. Energy storage deployment should be combined with intermittent renewable energy deployment. The periodicity often used in the literature corresponds to a daily periodicity, with storage during the night (~10 h) and restitution during a peak-load period (a few hours) or to seasonal periodicity. Two technologies are promising for massive energy storage: i) pumped hydro-energy storage and ii) CAES (Compressed Air Energy Storage).

This latter technology consists of using surplus of electricity to compress air when there is more supply than demand on the grid. The energy stored in the form of compressed air can be transformed into electricity when there is excess of demand compared to production. As explained in Mouli-Castillo et al. (2019) "electricity is generated by expanding the air through a gas turbine fired with methane gas […]. Conventional CAES releases approximately 228 g CO_2/kWh, less than the 388 g CO_2/kWh reported for the combined cycle gas turbines used in gas power plants. […] Ongoing research on a fossil-fuel-free CAES could extend its use beyond the lifespan of fossil fuels."

The compressed air can be stored either at the surface in steel tanks (but this raises surface occupation issues and safety challenges) or underground. For underground storage, different options exist:

- CAES-C (CAES in caverns). There are two commercial CAES plants, Huntorf in Germany and McIntosh in the USA with storage in underground caverns mined from salt (Mouli-Castillo et al., 2019).
- CAES-PM (CAES in Porous Media) or CAES-A (CAES in Aquifers): the concept uses a vertical well to inject compressed air into deep aquifers (e.g. Mouli-Castillo et al., 2019). It has not yet been demonstrated.
- In underground tanks[11].

Some authors have proposed to use CO_2 to improve this latter concept. When using CO_2, the problem of loss of mass in the reservoir can be seen positively since it contributes to CO_2 storage.

- CO_2 might be used as the energy carrier fluid, instead of air (Jiang et al., 2017; Li et al., 2020). In this case, the concept is called CCES (Compressed CO_2 Energy Storage) or CCES-A (CCES in Aquifers) or CCES-PM (CCES in Porous Media), see Figure 42. The energy storage density of compressed CO_2 is far greater than that of the air, thus making the use of CO_2 interesting. Thermodynamic analyses have been carried out for transcritical state (Liu et al., 2019; Hao et al., 2020) or supercritical state, highlighting the advantages of using CO_2. Li et al., 2022 highlighted some other advantages: CCES-A absorbs heat from the surroundings, while CAES-A continuously loses heat; the reservoir pressure of CCES-A is lower, with a lower cracking risk; CCES-A requires only 11.8% of the floor space of CAES-A; the average energy efficiency of CCES-A is 20% higher than that of CAES-A. As a potential drawback of using CO_2, it should be noted that geochemical phenomena are likely to be favoured by CO_2, possibly inducing undesirable consequences

[11] www.aug-wind.com

(Iloejesi and Beckingham, 2021). It should be noted that using CO_2 raises additional issues when CO_2 is depressurized (for instance storage in a surface vessel).

- Example of a case study (Li et al., 2020) with supercritical CO_2: depth around 1600 m, injection 54 kg/s during 12 hours, production 216 kg/s for 3 hours, round-trip energy efficiency between 95% and 105% (efficiency could exceed 100% due to heat transfer).
- CO_2 might be used as a cushion gas (with air being the exploited gas). It is injected before the cyclic utilization of compressed air to reduce the air mass and to improve energy efficiency (Oldenburg and Pan, 2013, p. 2).

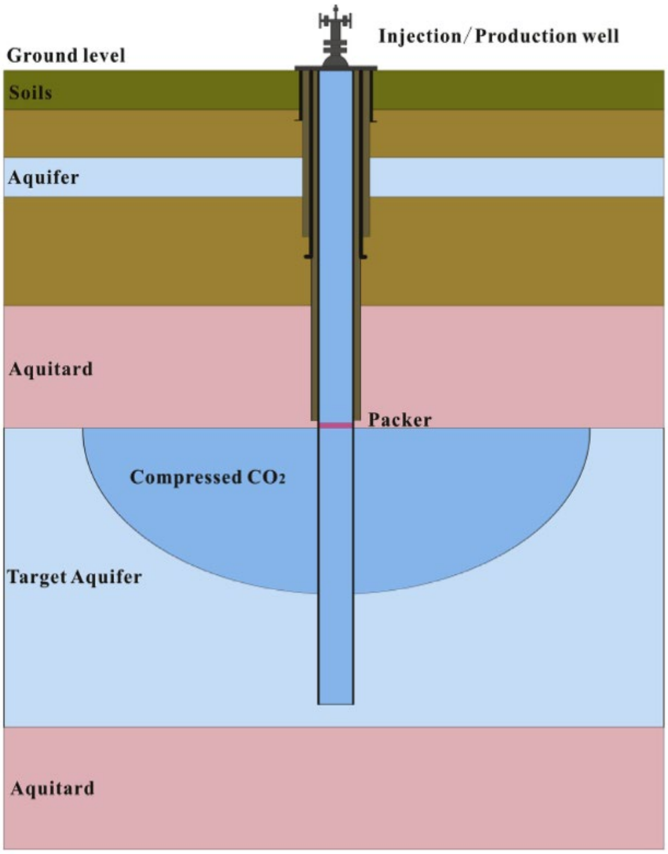


Figure 42. Concept model of CCES-A (Li et al., 2020)

Zhang and Wang (2017) propose an overview of the performances of the concepts using CO_2 (liquid CCES, transcritical CCES, CCES with storage in saline aquifer) by comparison with other underground technologies. The very high energy density of CO_2 offers promising perspectives, as illustrated in Table 11.

Table 11. Characteristics of different kinds of underground storage (Zhang and Wang, 2017)

Table I. Characters of different kinds of CAES, ETES (TEES), and CCES systems.

System	Round trip efficiency (%)	Energy density (kWh/m^3)	Main drawbacks
Conventional CAES	42, 54 (with recuperator) [6]	2–6 [17]	Fuel combustion and large storage volume in fixed and rigid reservoir
Adiabatic CAES	Around 70 [18]	Similar to conventional CAES [17]	Low energy density
Isobaric CAES with PHS [12]	Higher in CAES part but lower in hydraulic part	Higher than conventional CAES	Dependence on geographical conditions
Underwater CAES [13]	Up to 71	Higher than conventional CAES	Dependence on geographical conditions
Liquid air energy storage [14]	Below 50	Higher than conventional CAES	Low cycle efficiency
Supercritical CAES [15]	67.41	96	High cost of extremely low temperature for liquid air storage
Compressed air storage with humidification [16]	Above 60	Similar to conventional CAES	Much water consumption and low energy density
ETES/TEES	Up to 64 [19]	About 10 [20]	Complicated operations of multi-tank heat storage and ice generation
Isothermal TEES [20]	Around 70	14–15	Complicated machinery and operation
Liquid CCES [21]	56.64	36.12	Limited round trip efficiency
Transcritical CCES [22]	60.69	8.07	Complicated thermal storage technique
CCES with saline aquifer storage [23]	63.35 for transcritical operation and 62.28 for supercritical operation	497.68 for transcritical operation and 255.20 for supercritical operation	Dependence on the geographical conditions and use of fossil fuel

CAES, compressed air energy storage; ETES, electrothermal energy storage; TEES, thermo-electrical energy storage; CCES, compressed CO_2 energy storage.

3.4.2 *Closed-loop geothermal exploitation with supercritical CO_2 as a working fluid*

Foreword: This technology is not included in the present review since there is no storage of CO_2 (CO_2 is only used as a working fluid in a confined circuit during operations).

A review of this concept is proposed by Budiono et al. (2022). The concept is referred to as Closed-Loop Geothermal Systems (CLGS): "the working fluids do not come into direct contact with the reservoir. The main mode of heat transfer is the conduction between the reservoir and working fluid across well casings and cement. […] There are two types of CLGS: (1) coaxial CLGS (CCLGS) and (2) U-shape CLGS (UCLGS)." This technology aims notably heat mining in non-trivial geological contexts, which would otherwise be exploited through EGS technologies. Using closed-loop systems limit the risk of induced seismicity and allows projects to be de-risked by reducing to a manageable level a number of issues (the permeability has less/limited influence on performance, no geochemical interactions, etc.).
Some authors propose to use CO_2 as a working fluid (see Figure 43 in a U-Shape system or Figure 44 in a horizontal well). The characteristics of CO_2 enable the development of a thermosiphon effect, which increases efficiency. After the initial filling, there is no need to add CO_2 to the system. No CO_2 is stored underground at project closure. A demonstrator has been proposed at the Coso Geothermal Field in the USA (Amaya et al., 2020), developed by GreenFire Energy, with two demonstration periods in 2019. In this demonstration, supercritical CO_2 circulates through a 330-metre tube-in-tube heat exchanger (a down borehole heat exchanger DBHE). The modelling approach was validated using results from this first pilot. It is planned to perform future work to extend the modelling to consider other wells and closed-loop configurations and to carry out techno-economic analysis.

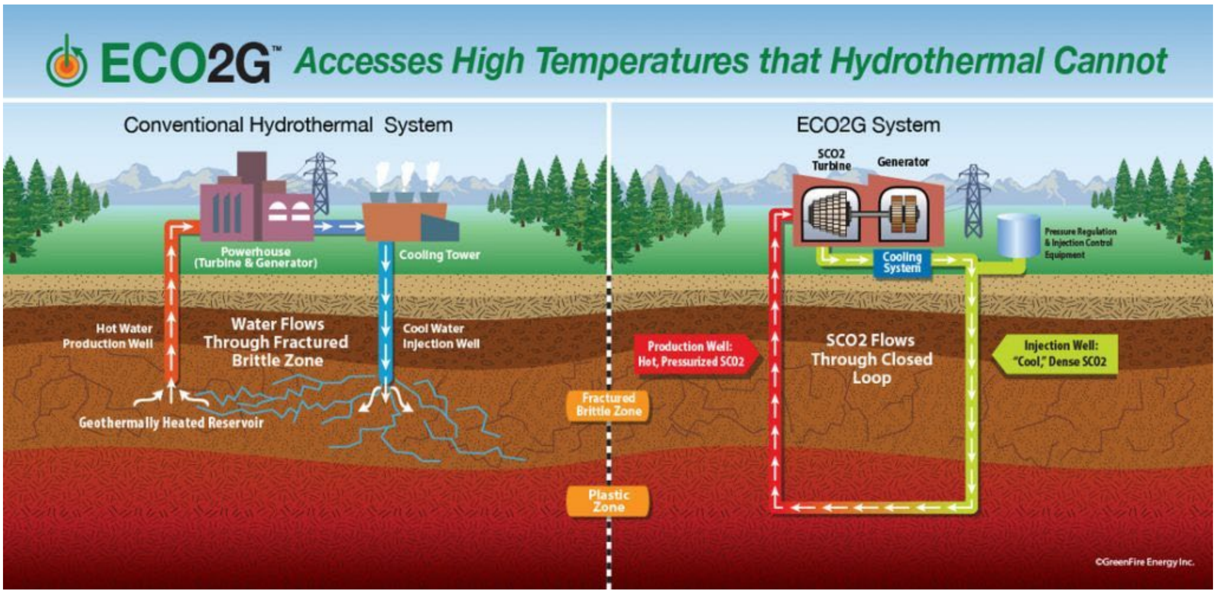


Figure 43. Illustration of the ECO2G concept with U-shape Closed-Loop Geothermal System (GreenFire Energy[12])

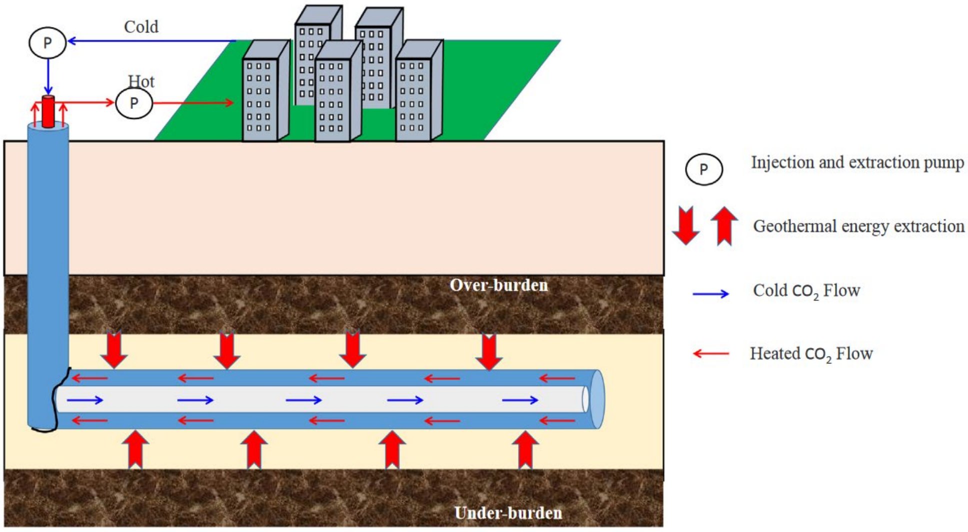


Figure 44. A schematic of geothermal energy extraction in closed loop system using an abandoned horizontal well (Sun et al., 2018)

[12] https://www.piensageotermia.com/oferta-laboral-project-manager-geothermal-demonstration-project-para-greenfire-energy/ , consulted October 6th, 2022

4 Elaboration of Key Performance Indicators (KPI) to compare concepts and conception of infographics to convey the results

Besides providing an overview of hybrid concepts of CO_2 storage and geothermal energy, a major objective of this report is to propose a framework for comparing their potential performance and merits. The main outcome of these comparisons is presented as supplementary material in the form of i) a spreadsheet that synthesizes all the KPIs
defined in this chapter for the concepts presented in chapter 3; and ii) a slide deck presenting infographics where the relative merits of the concepts are plotted for the indicators described below. The spreadsheet and slide deck are compiled in Annexes 1 and 2, respectively.

The methods developed for these supplementary materials are explained in this chapter. First we describe the development of a set of KPI and apply them to each concept. We summarize the outcome of this evaluation in a synthesis table. We then explain the concept that underpins the infographics.

4.1 Method for elaboration of KPI and notation scale

4.1.1 *KPI*

The objective was to define a set of characterization and performance indicators to identify the (surface and subsurface) settings that are most suitable for each concept and to give an overview of the main characteristics and logistical implications.

Characterization indicators have already been introduced in chapter 3, in the form of tables entitled "characteristics". In order to define these indicators, we identified from the literature the main information provided on the different concepts.

Performance criteria have already been introduced in section 0, in tables entitled "advantages, drawbacks and challenges". In order to identify these criteria, we used a methodology that we developed and applied on an internal project at BRGM that evaluated the performance in subsurface applications. To the extent possible, we propose a set of criteria that enables comparison of the reviewed concepts based on available information provided and criteria that serve as differentiators between the various technologies.

4.1.2 *Notation scales*

Characterization indicators are of two types. Firstly, there are quantitative indicators (e.g. depth), for which it was generally possible to identify a range of values in the literature, taking into account the plausible range of values foreseen for deployment and/or the range of uncertainties stemming from lack of knowledge (epistemic uncertainty). Secondly, we list qualitative indicators (e.g. geology), which are more of a descriptive nature.

When developing performance criteria, it was difficult to identify quantitative indicators that measure the performance owing to a general lack of pilot and/or demonstration projects. In principle, some performance criteria are amenable to be quantitatively measured; for instance, the criterion "the concept should present a worldwide potential as high as possible for CO_2 storage" (respectively for geothermal energy production), a quantitative direct indicator is "worldwide potential of storage in Gigatons" (for geothermal: "worldwide installed capacity of power generation or heat supply in GW"). However, the available literature does not provide such information, making a meaningful comparison across all concepts impossible. Also, even if such information were available for only a subset of the concepts, this is of limited interest for the objective of comparison. Instead, we use for each criterion an ad-hoc indicator "relative measure of performance on criterion X".

In terms of scaling, we have used a semi-qualitative scale, inspired by the "Likert scale"[13], instead of a normed scale. The maximal (best performance) score is 5 and the minimal score is 1. In order to establish the meaning of the notation scale, we first considered the different concepts and identified if there is disparity or not (by disparity we mean different performance for the different concepts). In case of disparity, we identified the outperformers and the reasons why they outperform. We provide some qualitative sentences to denote a good/bad performance (Figure 45). It allows the definition of the maximal score and of the minimal score. Then we establish nuance with intermediate values and use comparison between concepts and between the qualitative arguments in order to propose a notation (this might require some iteration).

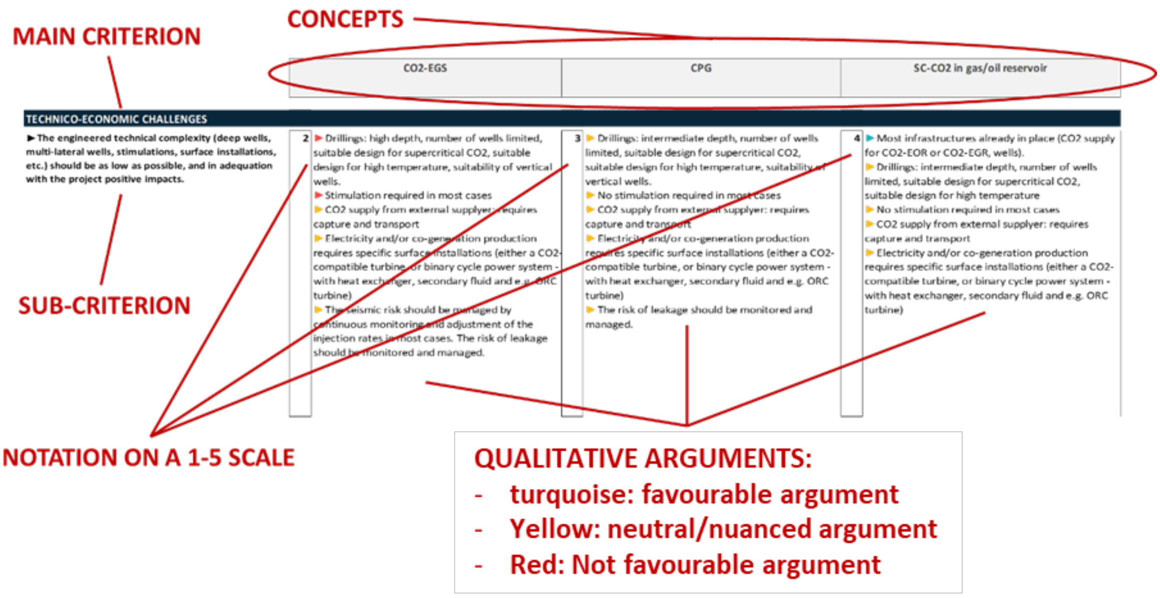


Figure 45. Illustration of the spreadsheet used for evaluation of performance criteria

We undertook this analysis during two brainstorming sessions, one internal at BRGM (5 participants) and one involving the same BRGM team (5 participants) plus IEAGHG staff (2 participants). We describe criteria and the notations in detail below. The results of this work with evaluations is available in a spreadsheet file reported in Appendix 8.1.

Some criteria can be further broken down into a series of sub-criteria (non-exhaustive list). For example, the umbrella criterion "limit adverse environmental consequences (risks and impacts)" has the following sub-criteria:

- surface footprint should be limited
- water consumption should be limited
- containment of CO_2 should be guaranteed for CCS objectives and safety issues (leakage)
- seismic risk should be low (either naturally low or well-managed)

First, we scored each sub-criterion. In order to provide a score for the umbrella criterion, and then we calculated the arithmetic average of the sub-criteria scores. This approach is likely to introduce a bias, because we did not calibrate scales and we simply suggest equal weighting for each of the sub-criteria. Providing a score for the umbrella criterion has the advantage of

[13] https://en.wikipedia.org/wiki/Likert_scale

providing a ballpark comparison without having to consider the full list of sub-criteria, which would be unpractical. However, the authors are aware that this brings limitations when interpreting the results. The notation scales were elaborated empirically for the sake of the exercise only.

4.2 Set of Key Performance Indicators

4.2.1 *Overview of criteria and sub-criteria*

It should be noted that criteria are defined at different levels; first-level criteria are more general, whereas sub-criteria are more focused on technical/environmental/economic aspects. Some overlap occurs between some items, but this is not considered as a problem since the comparison is made only criterion by criterion, without score agglomeration.

The main criteria and sub-criteria are:

- The concept should have ambitious objectives, and high worldwide replicability potential. Summarized in "AMBITIONS & REPLICABILITY".
  ►The overall objective of the concept is to contribute as much as possible to energy supply and demand as well as environmental challenges imposed by climate change (produce renewable energy, if possible with near-zero emissions, store CO_2 to contribute to climate-change mitigation and CO_2 removal, offer energy storage service that contribute to system decarbonation)
  ►The concept should be easily replicable
  ►The concept should present a worldwide potential as high as possible for energy supply (performance of an individual plant x replicability potential) to significantly contribute to global energy supply and environmental challenges.
  ►The concept should present a worldwide potential as high as possible for CO_2 storage (performance of an individual plant x replicability potential) to significantly contribute to global energy supply and environmental challenges.
- The concept should be easy to integrate, as modular and as scalable as possible. Summarized in "INTEGRATION, MODULARITY & SCALABILITY".
  ►Upstream requirements: If the concept requires an external supply (e.g. CO_2 from external emitters), the quantitative and qualitative requirements should be in accordance with realistic supply options so that the concept can be integrated in the overall system.
  ►Downstream requirements:
  i. the quantitative and qualitative characteristics of energy production/storage should integrate into the energy system;
  ii. handling of other outputs (if any) should be practically feasible.
  ►The concept should be as scalable and adaptable as possible. The concept should be as modular as possible, "plug&play variant" would facilitate the integration ("plug & play" characterizes a technology that can be deployed easily in a new location and that will work perfectly once deployed, without reconfiguration or adjustment to deal with specific features).
- The concept should be perceived positively by stakeholders. Summarized in "PERCEPTION BY STAKEHOLDERS"
  ►Legitimacy of the concept should be as high as possible for the different stakeholders.
- The concept should be as mature as possible with limited technical and non-technical barriers for rapid deployment. Summarized in "READINESS".
  ►Proof of performance and of safety should be as high as possible.
- The concept should limit adverse environmental consequences (risks and impacts. Summarized in "ENVIRONMENTAL RISKS & IMPACTS".

►Surface footprint should be limited
►Water consumption should be limited
►Containment of CO_2 should be guaranteed for the CCS objective and safety issues (leakage)
►Seismic risk should be low (either naturally low or well-managed).

- The technical complexity and the scientific challenges that need to be addressed should be as limited as possible. Summarized in "TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES"
  ►Engineered technical complexity (deep wells, multi-lateral wells, stimulations, surface installations, etc.) should be as low as possible, and in accordancewith the project positive impacts.
  ►Operational complexity should be as low as possible. Thus thermo-hydro-mechanical phenomena, microbio-geochemical phenomena, management of reservoir, production and facilities engineering during service life, should be well understood in order to avoid detrimental dysfunctions (examples: thermal breakthrough, non-constant heat recovery, consequences of impurities, seismicity, precipitation and clogging in the near-wells and scaling in reservoir and wells, corrosion in wells and surface installations, perturbation in the reservoir).
- The business model for deploying the concept should be performing and robust. Summarized in "CREDIBLE PATH TO COMMERCIALITY"
  ►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.
  ►The path to a competitive unit technical cost should be credible and reasonable (high investment costs 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).

Another important criterion could be "the concept should not encounter hurdles due to regulation". Regulation was deliberately not considered in this study for the following reasons: i) it is highly country-dependent; ii) there is no literature data readily available and gathering additional data to enable an evaluation requires substantial work which is outside the scope of this study; iii) regulations will evolve in order to adapt to new technologies. In our opinion, it is not possible to propose differentiating evaluations for each of the concepts. The criterion would add no value in this comparative exercise. However, we emphasize that pushing further the analysis would require a focus on regulations.

4.2.2 *Ambitions and replicability*

Sub-criterion 1

►The overall objective of the concept should as much as possible contribute to energy and environmental challenges raised by climate change (produce renewable energy, if possible with near-zero emissions, store CO_2 to contribute to climate-change mitigation, offer energy storage service that contribute to system decarbonation).

Scores are attributed as follows:

1	The concept produces non-intermittent geothermal energy. If the geothermal fluid contains CO_2 or other NCG, it is vented to the atmosphere.
2	The concept produces non-intermittent geothermal energy with near-zero emissions. Or

	The concept performs CO_2-storage with no parasitic load supplied by fossil fuels.
3	The concept produces non-intermittent geothermal energy and stores CO_2 from external emitter with storage quantity limited by solubility limit. Or The concept produces non-intermittent geothermal energy with near-zero emissions, and produces electricity from methane contained in the geothermal fluid.
4	The concept produces non-intermittent geothermal energy and stores CO_2 from external emitter in the supercritical form. Or The concept produces non-intermittent geothermal energy and stores CO_2 from biomass external emitter, leading to negative CO_2 emissions.
5	The concept produces non-intermittent geothermal energy and stores CO_2 from external emitter and proposes storage services.

Sub-criterion 2

►The concept should be easily replicable considering the required underground conditions. The replicability potential of some concepts is presented in scientific articles, but authors use different approaches and different assumptions, so that making the figures comparable requires considerable additional work. A qualitative indicator was used with the following notation. It should be noted that the notation scale was empirically established considering the results of the first expert brainstorming session, considering arguments that were considered favourable/not favourable and the extent to which these arguments modify the notation. The starting point (here a score of 4) was chosen to use the whole notation scale and to obtain scores that coincide with scores elicited from experts.
From an initial score of 4:

- +1 if the concept uses supercritical CO_2 as a heat carrier, because it allows targeting a less permeable reservoir formation (higher mobility due to lower viscosity), which increases the replicability[14].
- +1 if the concept targets ubiquitous geothermal resources at reservoir temperatures less than 90°C.
- -1 if the concept uses supercritical CO_2 because it constrains the depth and the necessity of a tight caprock[15].
- -1 if the concept is constrained by specific subsurface features (e.g. presence of natural gas).
- - 2 if the concept is constrained by very specific geological features (e.g. ultramafic rocks, former gas reservoir exploited with EGR)
- - 1 if the concept is still technically very challenging, even for "similar conventional" exploitation, and that the theoretical replicability should thus be considered cautiously.
- -1 if the system requires water handling (water consumption or water disposal in another location)
- - 1 if the system requires two aquifers or a very large aquifer.

Sub-criterion 3 and 4

[14] This item is described for the sake of exhaustiveness in order to mention that use of $scCO_2$ can be accounted for positively (+1). Note that item#3 highlights the negative impact of using $scCO_2$ (-1) because it requires more constrained geological features of the reservoir. At the end, using $scCO_2$ will then result in a null impact on the global mark (0 = +1 -1)

[15] This item is described for the sake of exhaustiveness in order to mention that use of $scCO_2$ can be accounted for negatively (-1). Note that item#1 highlights the positive impact of using $scCO_2$ (+1) because it requires less constrained hydrogeological properties of the reservoir. At the end, using $scCO_2$ will then result in a null impact on the global mark (0 = -1 +1)

►The concept should present a worldwide potential as high as possible for energy production (individual potential x replicability potential) to significantly contribute to global energy supply and environmental challenges.
►The concept should present a worldwide potential as high as possible for CO_2 storage (individual potential x replicability potential) to significantly contribute to global energy supply and environmental challenges.

These criteria are redundant with the previous one regarding the replicability potential, but here we consider to what extent the concept contributes to geothermal energy production (respectively to CO_2 storage), taking into account the contribution of a single deployment for energy production (respectively to CO_2 storage). The intention is to differentiate the potential for geothermal energy production / CCS.
We start with the score obtained for the previous criterion and we adjust the scores as follows:

- +2 if the concept provides more than 50 Mt CO_2 storage over 30 years (respectively capacity over 50 MWe).
- +1 if the concept provides more than 10 Mt CO_2 storage over 30 years (respectively capacity over 10 MWe).
- Unchanged if the concept provides between 2 and 10 Mt CO_2 storage over 30 years (respectively capacity in the range of 2-10 MWe).
- -1 if the concept provides less than 2 Mt CO_2 storage over 30 years (respectively capacity below 2 MWe).

4.2.3 *Integration, modularity and scalability*

Sub-criterion 1

►Upstream requirements (in particular CO_2 requirements): If the concept requires an external supply (e.g. CO_2 from external emitter), the quantitative and qualitative requirements should be in accordance with possible practical supply in order to be integrated within the overall system.

The following notation is used: addition of a point for facilitating conditions and removal of a point for additional constraints.

1	unused
2	During initialization, the concept requires an external CO_2 flux that is higher than during operations.
3	The concept requires CO_2 flow that might be variable from an external medium/large emitter.
4	The concept requires continuous CO_2 flux from an external medium/large emitter.
5	No external requirements Or The concept requires continuous CO_2 flux from an external small emitter (the density of small emitters is higher than the density of medium/large emitters).

Sub-criterion 2

►Downstream requirements: i) the quantitative and qualitative characteristics of energy production/storage should be such that the concept can be integrated into the energy system; ii) handling of other outputs (if any) should be practically feasible.

The following notation is used:

1	unused

2	The technology delivers heat at high scale (over ~5-10 MWth) that should feed local needs.
3	The technology delivers heat at intermediate scale (a few MWth) that should feed local needs.
4	The technology produces both non-intermittent renewable electricity and heat. Heat should feed local needs. Or The technology delivers non-intermittent renewable electricity and electricity storage services, which requires more complexity for integration in the grid than electricity production only. Or The technology delivers heat for local needs already well identified (e.g. carbon capture process).
5	The technology delivers mainly non-intermittent renewable electricity. Valorization of possibly co-produced heat should be considered regarding local needs in order to improve energy efficiency.

Sub-criterion 3

►The concept should be as scalable and adaptable as possible. The concept should be as modular as possible, "plug&play" would facilitate the integration.

Starting from an initial score of 4:

- +1 if the concept uses/shares already existing multidisciplinary datasets (on reservoir parameters) and infrastructure.
- +1 if the design of the system already integrates modular/ plug&play design.
- -1 if the concept is limited to large-scale implementation (-2 if very large scale).
- -1 if the concept requires a high level of one-of-a-kind facilities that prevents developing a plug&play system in the short term.
- -1 if the sizing of the system is imposed by technical constraints rather than by clients' needs (e.g. geothermal valorization of CO_2-EGR reservoirs).

4.2.4 *Perception by stakeholders*

►Legitimacy of the concept should be as high as possible for the different stakeholders.

Political and societal barriers are indirectly related. Previous studies have proposed to use the concepts of credibility, legitimacy and governance to see how emerging technologies may be adopted by a territory (Chailleux, 2020; Gough and Mander, 2022).
The credibility of a technology represents its ability to hold its promises. It is already addressed in other criteria.
Governance can be assessed with regulatory and participation criteria. As mentioned above, considering regulation in the set of criteria is impractical because of the regulation differences between countries and the quantity of work, which would require analysis of local regulations on a case-by-case basis.

This is the reason why we focus this criterion on "legitimacy" and use this term.
The legitimacy of a solution relates to how this solution is perceived by various stakeholders, the pros and cons for the different groups considered. Focus here is placed particularly on local communities. Considering the limited amount of published information related to public perception for most concepts, the proposed notation should be considered with caution, as the actual perception from stakeholders depends on many factors that are specific and not generic (von Rothkirch and Ejderyan, 2021).

We consider a score of 3 by default. If there is reason to advocate legitimacy of the concept, we move the score to 4. If the concept has already been deployed without opposition, we provide a score of 5. If, on the contrary, there is reason to expect possible opposition, we decrease the score to 2.

4.2.5 *Readiness*

Foreword: it was agreed that it was best to avoid the use of the Technology Readiness Level (TRL) scale[16], commonly used by many organizations in the evaluation of research and innovation projects, for the following reasons:

- Numerous concepts are presented from a theoretical point of view and correspond to very low TRL. As numerous concepts are still at low TRL (1-4), this would not allow a proper distinction and comparison.
- Numerous concepts involve the combination of different sub-technologies/components, which have highly variable TRL. Evaluating the overall TRL of a composite technology is a challenging exercise.
- The perimeters of the different concepts presented in the literature review are different (for instance, some concepts focus only on the underground technology while others integrate the whole chain), and thus the comparison between these concepts would be biased.

►Proof of performance and of safety should be as high as possible.

As for the other criteria, we use an adhoc indicator with a 5-level scale, which does not correspond to TRL, but to a measure of readiness used within the present study.

From an initial score of 3:

- -1 if it relies on a technology that still encounters a number of challenges.
- +1 if it has already been demonstrated at pilot scale or at demonstrator scale for a short duration.
- +2 if it has already been demonstrated for several years.

4.2.6 *Environmental risks and impacts*

Impacts that relate to emissions (mainly global impact on climate change) are not covered here since it is already covered under criterion "ambitions and replicability".

Sub-criterion 1

►Surface footprint should be limited.

This criterion has limited interest for inter-comparison between different underground concepts since the great majority outperform on this sub-criterion. Nevertheless, we introduced it to highlight this benefit and to favour concepts that do not require surface storage in tanks. All concepts score 5 or 4 (the latter when a surface tank is needed).

Sub-criterion 2

►Water consumption should be limited.

Again, this criterion has limited importance for comparison since all technologies have a similar performances. Water is required for drilling operations, but during the exploitation phase, the need for water from an external resource is very limited as most of the water is supplied by the exploited brine. All concepts score 4.

[16] https://ec.europa.eu/research/participants/data/ref/h2020/other/wp/2016_2017/annexes/h2020-wp1617-annex-g-trl_en.pdf

Sub-criterion 3

►Containment of CO_2 should be guaranteed for the CCS objective and safety issues (leakage).

As detailed in section 2.6, safety is related to the phase of the injected CO_2 and the form of trapping. Thus, technologies that use CO_2 dissolved in water have a reduced risk level compared to technologies working with supercritical CO_2.

The following notations are used:

1	The CO_2 is stored in the supercritical form in a fractured medium.
2	The CO_2 is stored in the supercritical form in an aquifer or depleted reservoir, with large surface footprint for the plume.
3	The CO_2 is stored in the supercritical form in an aquifer or depleted reservoir, with limited surface footprint for the plume.
4	The CO_2 is stored in the dissolved form below a tight caprock.
5	The tightness of the reservoir has already been demonstrated over the very long term for gas storage. Or The concept drives to very rapid mineralization, which is the safest storage mechanism for CO_2.

Sub-criterion 4

►Seismic risk should be low (either naturally low or well-managed).

Underground operations tend to modify the characteristics of a reservoir by withdrawing and injecting hot and/or cold fluid from/into the underground. It creates stress changes that can cause micro-seismic events. Some other effects, like perturbations due to drilling, or redistribution of stress due to variations in fluid volume within the reservoir, can also cause induced events.

Microseismicity refers to seismic events with seismic moment magnitudes below 2-3, i.e. values that are detected by seismometers but not, or only slightly, felt by the general population. It is sometimes associated with geothermal developments and CO_2 storage activities. Operators generally have safety measures in place to minimize the risk of strongly felt or damaging seismic events. When caused by human activities, seismic events are defined as induced seismicity and should be distinguished from naturally occurring seismicity (IEAGHG, 2022).

Very limited information exists to assign scores, so we only adopted medium values in order to reflect the level of uncertainties. This prevents from being very affirmative at this stage, and considering the fact that seismicity is very site-specific.

The following notation is used:

1	/
2	The seismic risk is likely to be a technical challenge (because stimulations enhance permeability) requiring detailed monitoring and pressure management.
3	The seismic risk is manageable with current good practices and the geology is not prone to seismicity in most cases. However, a significant change of fluid volume occurs in the reservoir and a subsequent pressure increase might induce geomechanical perturbations.
4	The targeted geological contexts are not prone to seismicity. Volume changes are limited. Modifications of the pressure field are local.
5	/

4.2.7 *Technical complexity and scientific challenges*

Sub-criterion 1

►Engineered technical complexity (deep wells, multi-lateral wells, stimulations, surface installations, etc.) should be as low as possible, and in adequacy with the project positive impacts.

From an initial score of 5:

- -1 if it requires complex well and completions engineering such as horizontal wells or high depths wells;
- -1 if it requires dealing with high temperature (above 100°C);
- -1 if it requires stimulation;
- -1 if it requires dealing with supercritical CO_2;
- -1 if the surface installations are expected to be complex;
- +1 if it reuses existing infrastructures.

Sub-criterion 2

►Operational complexity should be as low as possible. The thermo-hydro-mechanical phenomena, as well as the microbial-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-well, scaling in wells, corrosion in wells and surface installations, perturbation in the reservoir).

From an initial score of 5:

- -1 if the concept targets great depths (lack of data, exploration more difficult);
- -1 if the concept targets heterogeneous formations;
- -1 if the system involves several phases (vapour/gas, liquid, supercritical, etc.) and components (H_2O, CO_2, hydrocarbons, other NCG)
- -1 if there is an important challenge to understand mechanical behaviour (e.g. seismicity), thus making THM coupling necessary;
- -1 if there is a high temperature difference between reinjection and initial temperature (more than 60°C);
- -1 if geochemistry and/or microbiology present major challenges;
- +1 if there is a large body of scientific, engineering and technical literature on understanding and modelling phenomena and processes.

4.2.8 *Credible path to commerciality*

Sub-criterion 1

►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.

From an initial score of 5:

- -1 if the risk is high before drilling, notably due to depth.
- -1 if there is a drilling complexity;
- -1 if the fluid circulation is a challenge (permeability, connection between injection and production well);
- -1 if the seismic risk is a challenge;
- -1 if there is additional complexity (detailed in the spreadsheet file case by case);
- -1 if the deep geothermal system operates with CO_2 instead of water, which has never been done so far.

Sub-criterion 2

►The path to a competitive unit technical cost should be credible and reasonable (high investment costs and initialization duration might be hurdles). The economic performance should be as robust as possible during the project life span (competitive operating costs, robust reliability and efficiency).

From an initial score of 4:

- -1 if the investment costs and the economic risk are high due to depth or complexity;
- -1 if the initialization period is low cost (no revenue for energy during initialization);
- -1 if revenue streams are likely to fluctuate;
- +1 if the business model benefits from multiple sources of revenue (heat/power revenue, energy services revenue, CO_2 storage revenue, etc.);
- +1 if the investment is very limited due to re-use of former infrastructures;
- Maintenance and operation costs should also be considered but due to a lack of data to differentiate concepts, they were not considered.

4.3 Summary of scores

Before discussing our summary of scores, we would like to emphasize that there is very little hard data available in the literature for several concepts. Hence, valuations are subject to expert judgements that are, to a large part, based on plausibility arguments. Readers are encouraged to apply the method themselves and arrive at their own assessment, which is quite likely to differ from ours.

Table 12. Summary of notations on criteria and sub-criteria for all technologies

	CO2-EGS	CPG	Heat mining with SC-CO2 in gas/oil reservoirs	CPG-ES	Earth Battery - CO2-BES/TES	Carbfix*-like concept	CO2-reinjection concept	CLEAG-like concept	CO2-DISSOLVED-like concept	Geothermal BECCS	CCS-driven concept	CCS with geothermal energy for capture process	Hybrid-energy systems	Synergetic dual use 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**	**3.5**	**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	5	4	4
►The concept should be easily replicable considering underground conditions required.	3	4	2	3	3	2	4	3	5	5	2	3	2	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	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	4	5	5
INTEGRATION, MODULARITY & SCALABILITY	**3.3**	**3**	**4**	**2.7**	**3**	**4.3**	**3.7**	**4**	**4**	**4.3**	**3.7**	**3.7**	**4**	**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	5	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	5	3	2
►The concept should be as scalable and adaptable as possible. ►Modularity and "Plug&play declination" would facilitate the integration.	2	2	3	2	1	4	3	5	4	4	3	3	2	3	3
PERCEPTION BY STAKEHOLDERS	**2**	**3**	**4**	**3**	**3**	**5**	**4**	**5**	**3**	**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	3
READINESS	**2**	**3**	**4**	**2**	**2**	**5**	**3**	**5**	**4**	**3**	**2**	**3**	**2**	**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	2	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**	**3.8**	**4**
►The surface footprint should be limited	5	5	5	5	4	5	5	5	5	4	5	5	5	5	5
►The water consumption should be limited	4	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	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	3	4
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	**1**	**3**	**3**	**2.5**	**2.5**	**4**	**3.5**	**4.5**	**4.5**	**3.5**	**3.5**	**3.5**	**3.5**	**3**	**3.5**
►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	2	2	4	4	5	5	4	4	4	4	3	4
►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	3
CREDIBLE PATH TO COMMERCIALITY	**1.5**	**3**	**4.5**	**2**	**2.5**	**4**	**3**	**4**	**4**	**4**	**2.5**	**3.5**	**3**	**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	2	4	4
►The investment cost should be reasonable (high investment cost and initialization duration might be 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	4

This table is available as supplementary material in a spreadsheet file.

A sheet is proposed to produce synthetic view on a limited personalized set of criteria. For instance, as illustrated in Figure 46, it is possible to make a comparison between technologies that are currently being demonstrated (two different views are possible, either with symbols or with figures).

	AMBITIONS & REPLICABILITY	INTEGRATION, MODULARITY & SCALABILITY	PERCEPTION BY STAKEHOLDERS	READINESS	ENVIRONMENTAL RISKS & IMPACTS	TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	CREDIBLE PATH TO COMMERCIALITY
CPG	◕	◑	◑	◑	◕	◑	◑
CO2-Dissolved-like concept	◕	◕	◑	◕	◕	●	◕
Geothermal BECCS	●	◕	◑	◑	◕	◕	◕
Synergetic use through dual uses in the same reservoir	◕	◑	◑	◑	◕	◑	◕
Synergy through pressure management	◕	◑	◑	◕	◕	◕	◕

	AMBITIONS & REPLICABILITY	INTEGRATION, MODULARITY & SCALABILITY	PERCEPTION BY STAKEHOLDERS	READINESS	ENVIRONMENTAL RISKS & IMPACTS	TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	CREDIBLE PATH TO COMMERCIALITY
CPG	4.3	3.0	3.0	3.0	3.8	3.0	3.0
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
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

Figure 46. Personalized outputs on main criteria for a personalized set of concepts

4.4 Elaboration of infographics

The infographics have been produced to summarise the key findings of the bibliographic review (chapter 3). The idea is to gather in a single page the main information (both qualitative and quantitative) for each of the concepts considered in this study, producing an illustrated and easy-to-read document, based on the same graphic symbols in order to facilitate a quick comparison between concepts.

In order to discuss and compare concepts aiming at providing services on both CCS and geothermal energy production, it appeared necessary to first elaborate a visual index enabling a quick view of the nature of the services proposed by each concept: does it provide a service that is more CCS oriented or geothermal energy oriented, or is it well balanced between both? This is detailed in section 4.4.1. Then we present individual infographics for each concept (section 4.4.2), and finally, synthetic diagrams with the positioning of all the technologies considered with respect to some key criteria (section 4.4.3).

4.4.1 *Elaboration of an index of services ratio*

In order to compare the contributions of the different concepts on the two main objectives (energy production and CO_2 storage), we elaborated an index of services ratio.

CO_2 storage can be expressed by the quantity of CO_2 stored over a given period. In the present study, it was chosen to express the service in Mt CO_2 over a 30-year life span (in order to smooth the non-constant storage, e.g. due to an initialization phase).
Energy production can be expressed by either electrical/thermal power capacity or quantity of thermal/electrical production over a given period. In the present study, it was chosen to express the service in MWe (most widespread unit used in the literature).

Our first idea was to convert the renewable energy produced in terms of CO_2 emissions avoided. Assuming a standard coal-fired power plant produces 30 tons of CO_2 per MWe per day (Randolph and Saar, 2011a), 1 MWe would then correspond to 0.33 Mt CO_2 over 30 years of continuous energy production. However, such a conversion underestimates the renewable energy production service, which contributes by itself to energy production, and not only to reduction of CO_2 emissions.

Thus, it appeared more relevant to use orders of magnitude of economic valorization of both services. The proposed index has been elaborated for the present study only.

In IEA (2020), the default assumption for carbon pricing that was chosen is a "moderate emission costs of 30 US$/t$CO_2$". It should be noted that this assumption is rather low if we consider global carbon dioxide emissions reductions to net zero by 2050 and the associated carbon pricing required (IEA, 2021), see Table 13.

Estimates for the LCOE are given in Figure 47 and Figure 48 (IEA, 2020). They vary between 40 and 200 $/MWhe. Focusing on renewable technologies, an order of magnitude slightly over 100 US$/MWhe is in line with the market, in particular for the geothermal market. For sake of simplicity, we chose to use 114 US$/MWhe, which yields to an exact equivalence between the service provided by a 1 MWe renewable geothermal power plant and the service provided by the storage of 1MtCO_2, over a period of 30 years for both services.
For concepts that produce thermal energy, which is not converted to electricity, the default value proposed by IEA[17] is 37US$/MWhth.

Table 13. CO_2 prices (US$/t$CO_2$) for net zero emissions by 2050, for electricity, industry and energy production sectors (IEA, 2021)

USD (2019) per tonne of CO_2	2025	2030	2040	2050
Advanced economies	75	130	205	250
Selected emerging market and developing economies*	45	90	160	200
Other emerging market and developing economies	3	15	35	55

* Includes China, Russia, Brazil and South Africa.

[17] https://www.iea.org/articles/levelised-cost-of-electricity-calculator

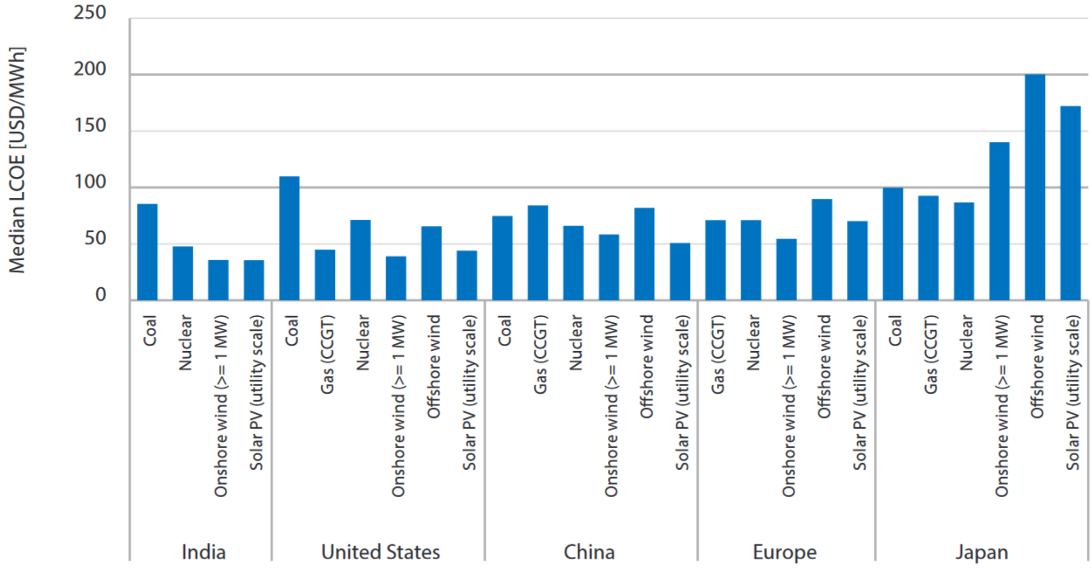


Figure 47. LCOE (US$/MWh) for different countries and different typologies of power plants, with discount rates at 7% (IEA, 2020)

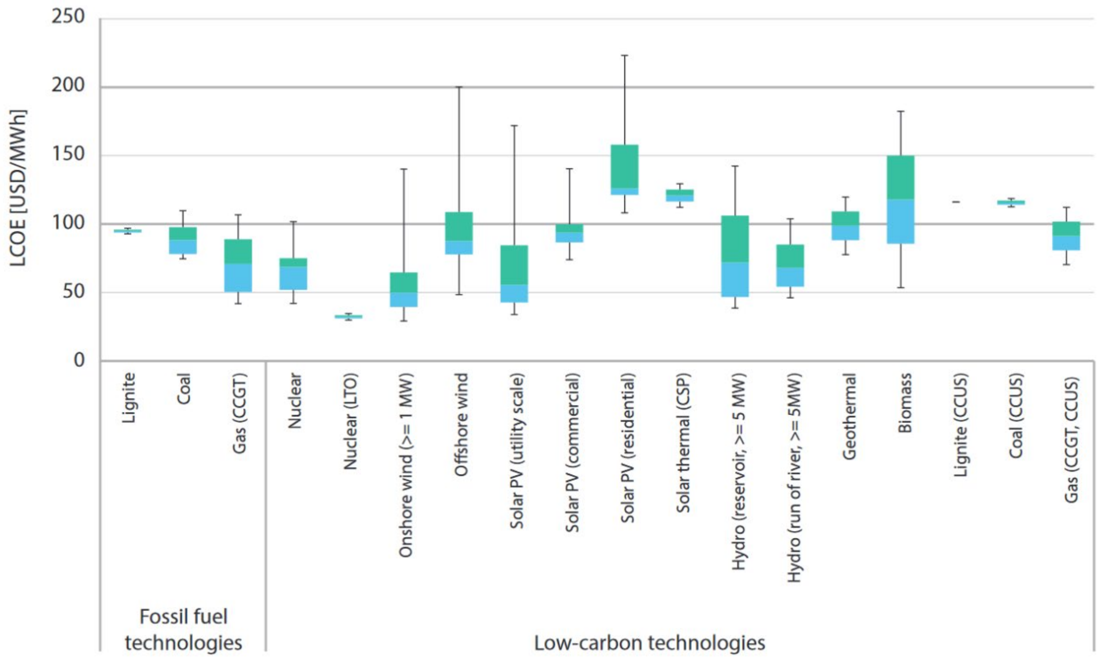


Figure 48. LCOE (US$/MWh) for different technologies (IEA, 2020)

The assumptions to define the index of services ratio are summarized in Table 14.

Table 14. Summary of assumptions used for defining the index of services ratio

	ASSUMPTIONS	REVENUES
CO_2 storage: 1 Mt over the life span	Carbon pricing: 30 US$/t$CO_2$ It should be noted that the cost of storage is only one of three major cost components (transport and capture being the other two). For concepts that focus on storage only, this revenue stream needs to be divided up by the capture facility operator, the transport operator, and the storage site operator. For fair comparison, the perimeter considered for each concept should include the CO_2 capture and transport. Since costs are not compared and the idea is only to weight the ratio of geothermal exploitation and CCS, this is not considered as a bias here.	$30x10^6$ US$
Electricity production corresponding to 1MWe	Over 30 years (common value for life span), 262 800 MWh_e (assuming permanent production). Sales price: 114 US$/MWhe.	$30x10^6$ US$
Heat production corresponding to 1MWth	Over 30 years (common value for life span), it produces 262,800 MWhe (assuming permanent production). The default sales price proposed by IEA is 37 US$/MWhth.	$10x10^6$ US$ (exact value 9.7, rounded for simplicity)

The indexes of service ratios for CO_2 storage (I_{CS}), electricity production (I_e), and heat production (I_{th}), are thus defined, respectively, as:

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

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

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

With Q_{CO2} being the valorized quantity of stored CO_2 over 30 years (in US$), P_e being the valorized electrical energy produced from a given power capacity (in US$), and $P_{th}/3$ being the valorized thermal energy produced from a given power capacity (in US$, accounting for a 3-times lower price for thermal energy with respect to electrical energy, see Table 14).

4.4.2 *Presentation of individual infographics*

For each concept, an individual infographic was elaborated to summarize its main features, as illustrated in Figure 49.

On the left are indicated the range of depths and temperature, the main fluid fluxes (CO_2 and/or brine), the main advantages and drawbacks, and some indication of the readiness level.
In the central part, a scheme summarizes the concept, with a description.

On the right are indicated the ranges of values for energy production and CO_2 storage. The index of services ratio (as defined in section 4.4.1) is represented in a pie chart. Finally, the implementation complexity is illustrated with different symbols.
We established and used common graphic symbols throughout the infographics, as explained in Figure 50.

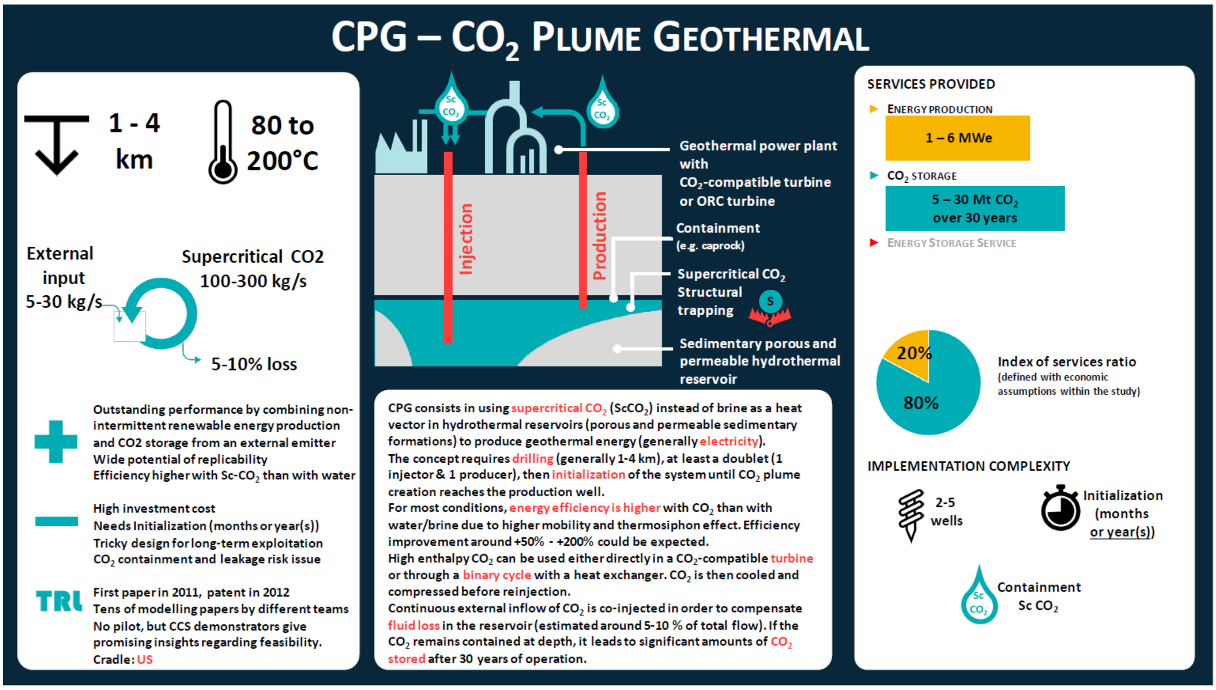


Figure 49. An example of an infographic presenting an individual concept (CPG)

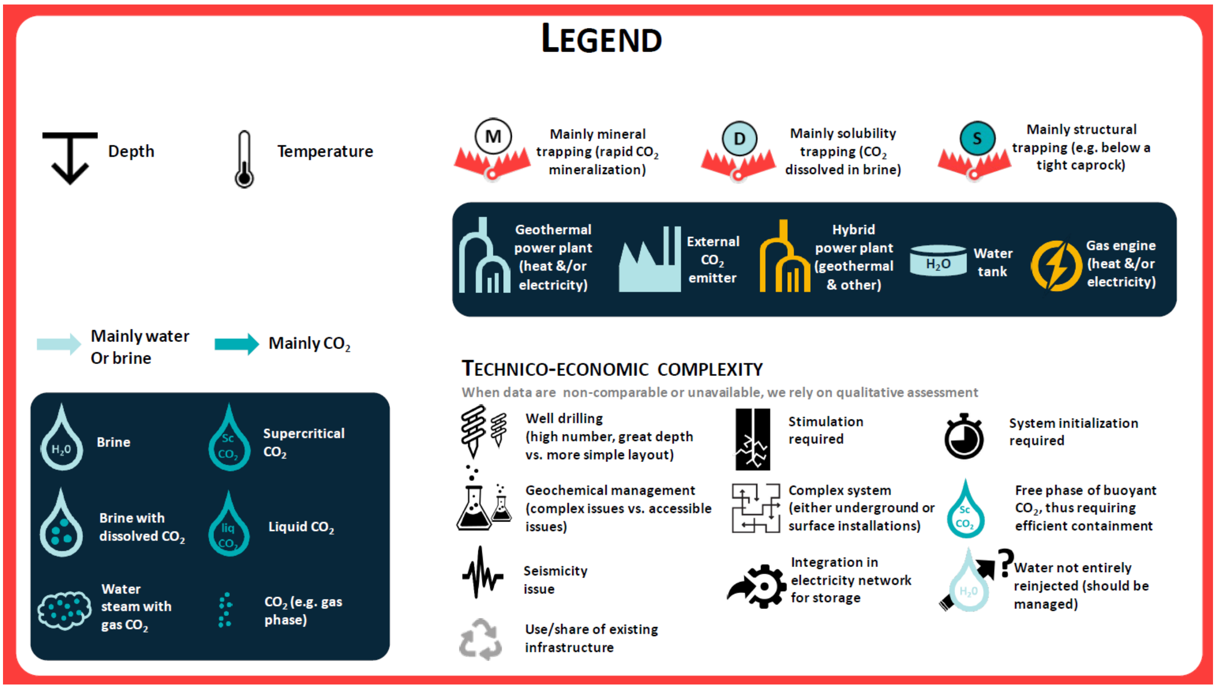


Figure 50. Infographic symbols used to present the individual concepts

The whole set of infographics is available in the form of a slide deck.

4.4.3 *Infographics comparing technologies*

A first overview (Figure 51) presents all concepts included in section 0 (including borderline concepts), on a 2-axis plot, considering the CO_2 storage capacity and the power capacity. The colour classification corresponds to the organization of the present report, as indicated on the colour scale in the right-hand part of the figure.

The second overview (Figure 52) takes the viewpoint of subsurface characteristics. Most concepts target a porous and permeable reservoir, overlain by a tight caprock. The ranges of reservoir permeability/porosity suitable for the different concepts appear to be similar, thus no classification was made depending on these parameters. A few concepts correspond to mixed permeability and /or impermeable rocks with fractures. The concepts that correspond to geological special features are indicated with stars (e.g. the fluid naturally contains CO_2 and/or methane, the rock is reactive). Concerning depth, all concepts are in the range 0.7-5 km, with many concepts targeting depths around 1.5-2.5 km.

In Figure 53, we represent the viewpoint of an external emitter. Assuming that an industrial emitter has a given range of emissions, and is interested to know which technologies could be appropriate for reducing its carbon footprint, we classified the concepts according to the external CO_2 emissions required.

In Figure 54, we present a map of main proponents involved on the different concepts.

In Figure 55, we classify concepts depending on the research effort and on progress on path to commerciality.

In Figure 56, concepts are classified depending on whether they are closer to CCS or to geothermal exploitation, based on the index evaluated as described in section 4.4.1.

Figure 57 and Figure 58 summarize the key features identified in Chapter 3 and Chapter 4:

- 5 concepts presented in Chapter 3 are intrinsically linked to specific geological features, which are either an opportunity (e.g. the suitability of the underground for rapid mineralization) or a constraint (e.g. the geothermal fluid contains CO_2).
- Other concepts require similar geological features (porous and permeable aquifer overlain by a caprock, at depth ~1-2.5 km). Among these concepts, the CPG concepts (pure CPG and CPG with energy storage) work with supercritical CO_2. A second category of concepts inject CO_2 in the dissolved form. Geothermal BECCS can be seen as a variation of the CO_2-DISSOLVED concept, where the external source of CO_2 comes from a biomass power plant, and the recovered heat is used by the biomass power plant. The concepts that use geothermal energy for capture and for storage in the dissolved form are also a variant with geothermal heat used for the capture process as an additional feature. The orders of magnitude for CO_2-DISSOLVED, Geothermal BECCS and CCS-driven concepts are very different, but the basic principle is similar. The last category corresponds to co-existence and synergy in the same reservoir with brine as geothermal fluid, and no use of brine as carrier for CO_2 storage.

These concepts can be considered as "competitive" in terms of use of the subsurface since they target similar reservoirs. Figure 59 presents a comparison of the main concepts that could be deployed in a permeable aquifer with a tight caprock. No concept outperforms on all criteria. Decision making will depend on the external emissions rate, the possibility for local heat valorization, more precise geological features. It would be necessary to carry out comparative scenarios for the set of appropriate concepts that fill the requirements in order to make a project specific decision.

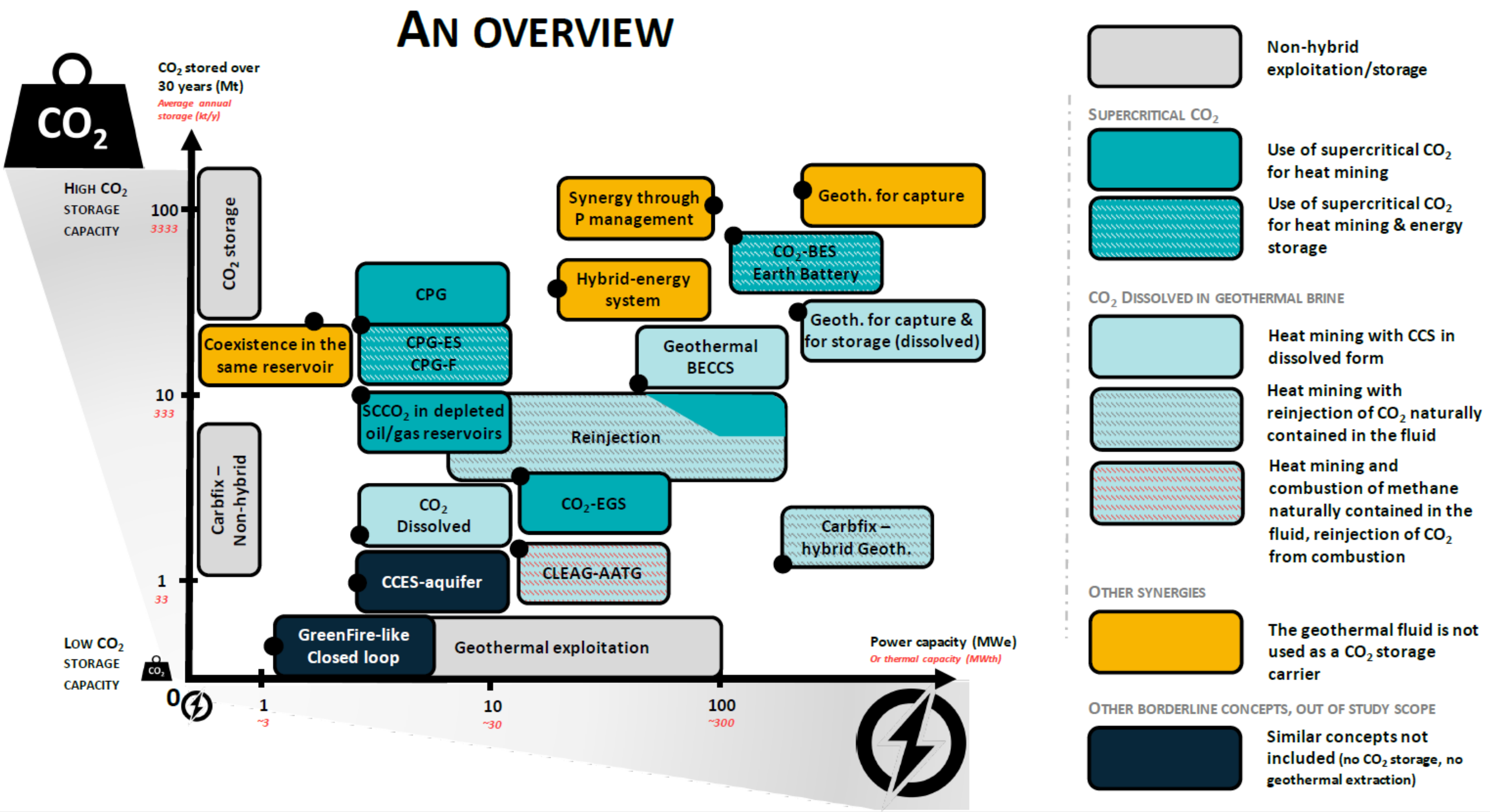


Figure 51. Overview of concepts according to CO_2 storage capacity and power capacity. "Geoth." Means geothermal energy extraction.

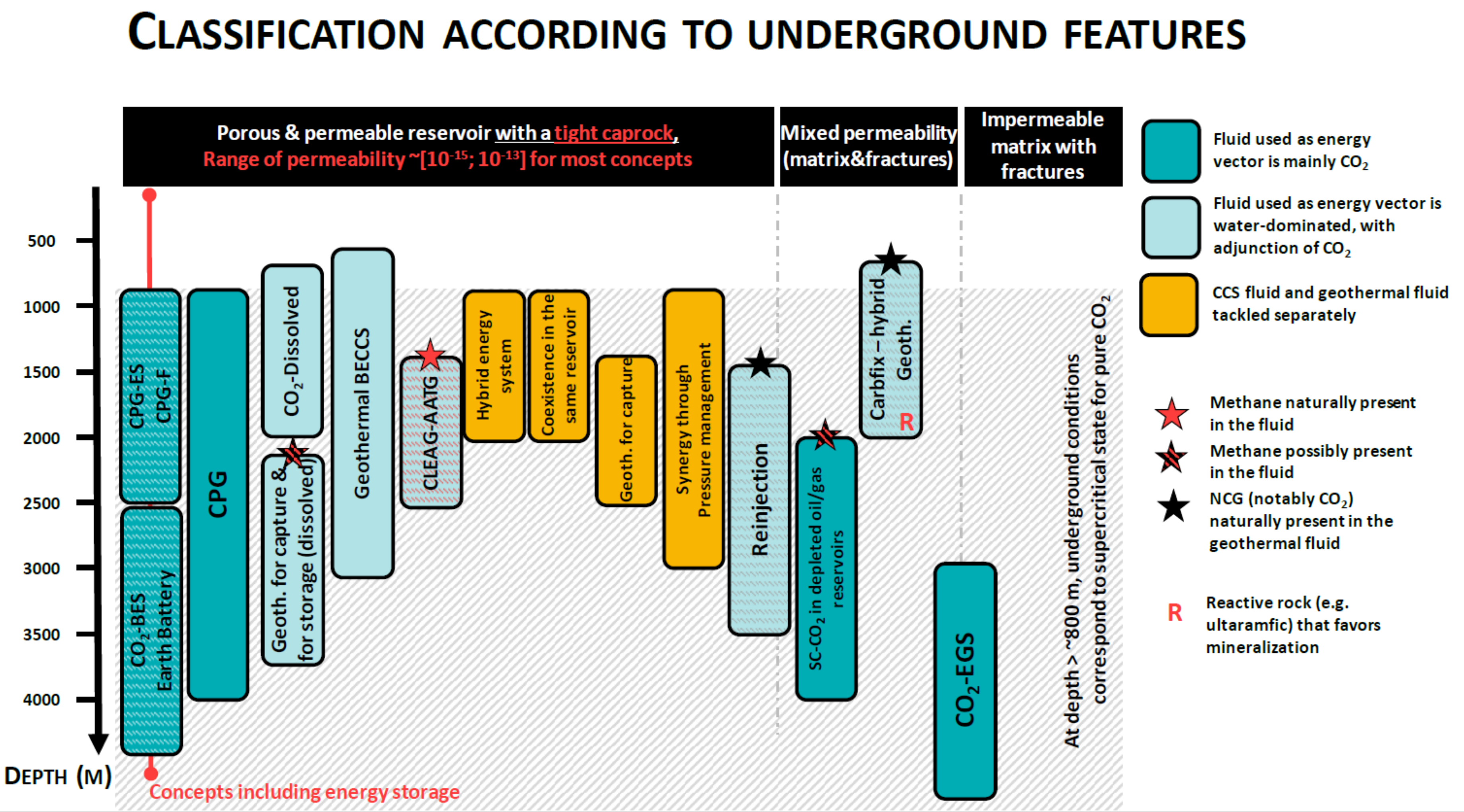


Figure 52. Overview of concepts according to underground characteristics

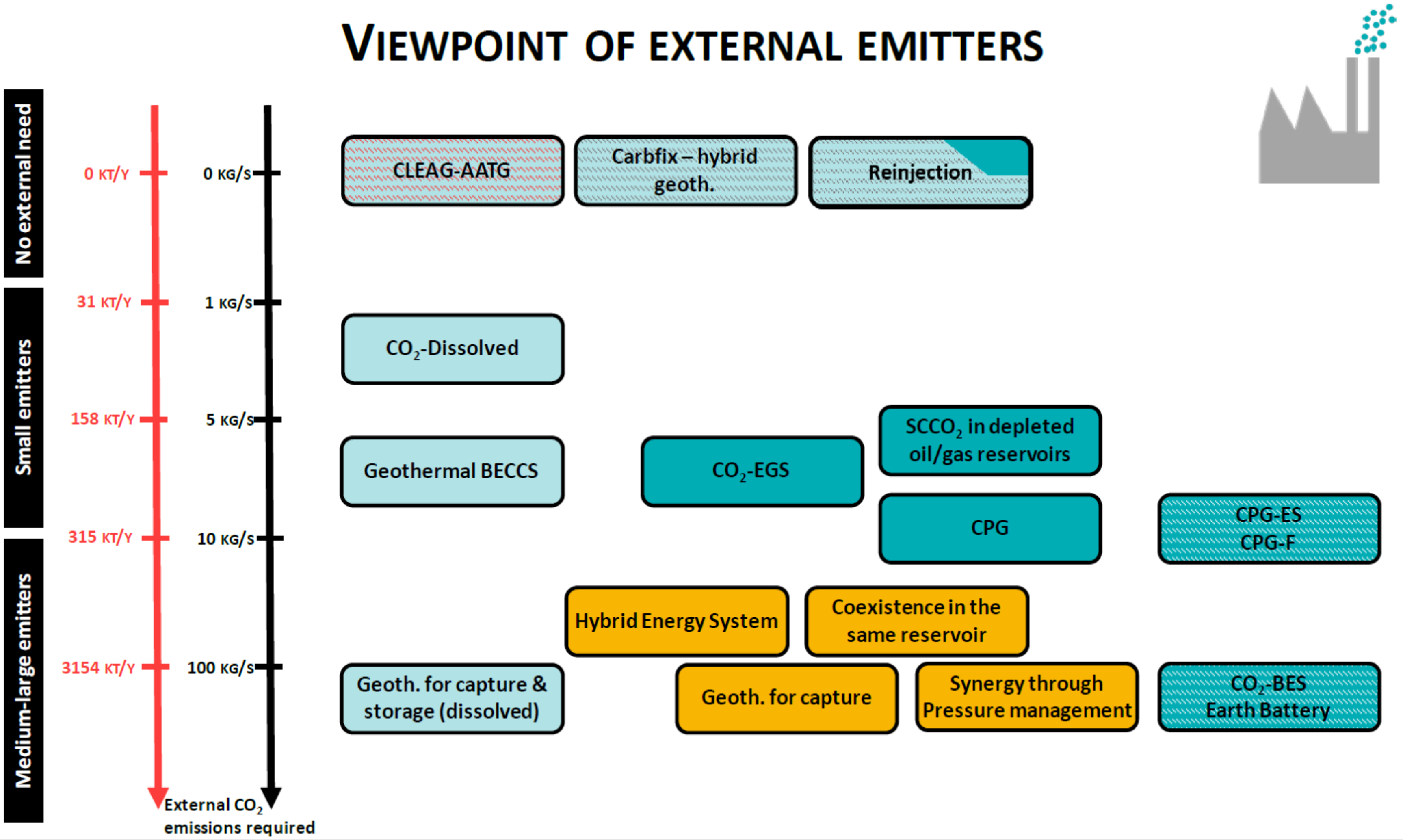


Figure 53. Overview of concepts according to requirements from a CO_2 external emitter

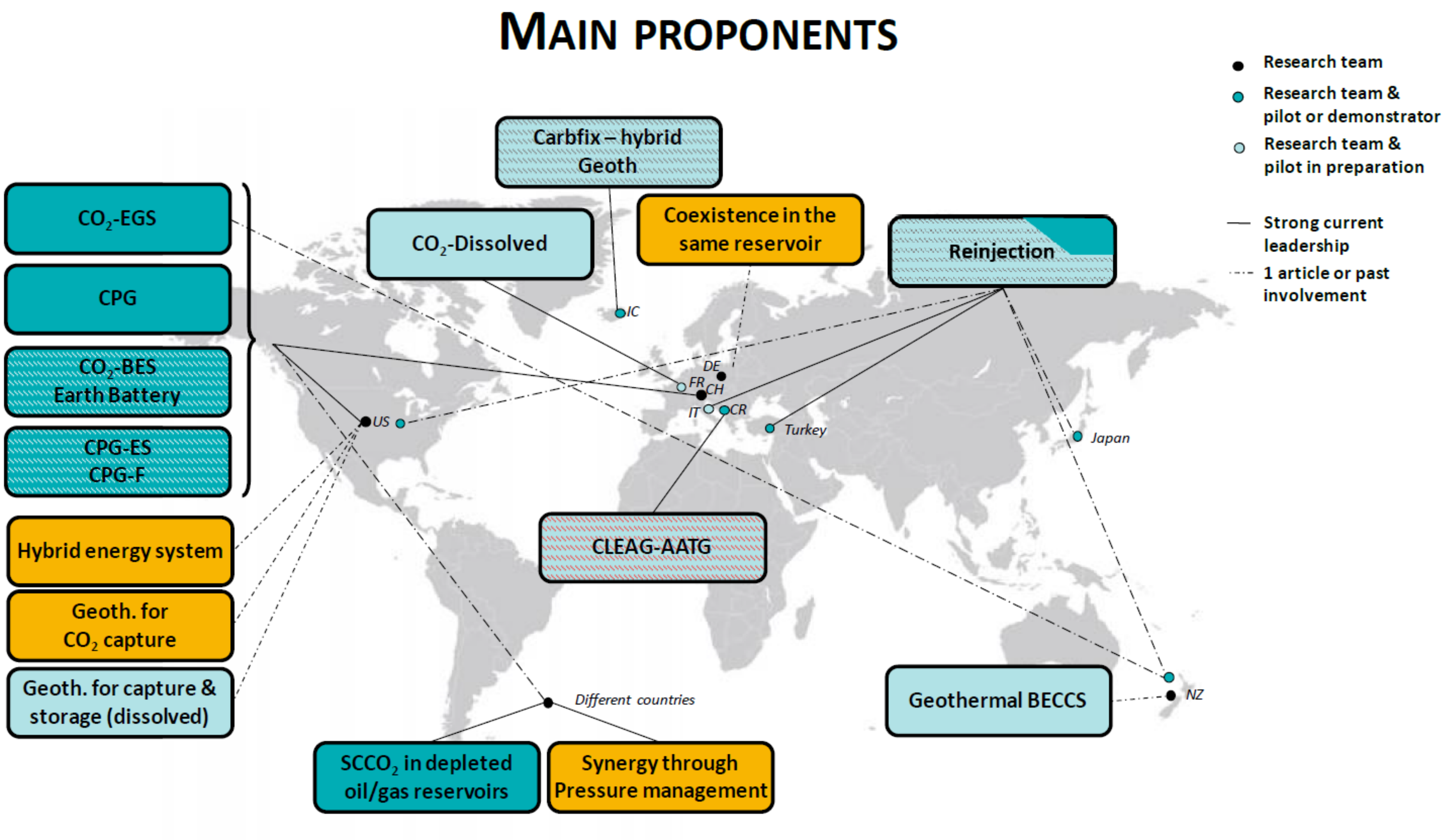


Figure 54. Map of main proponents involved in advancing the concepts

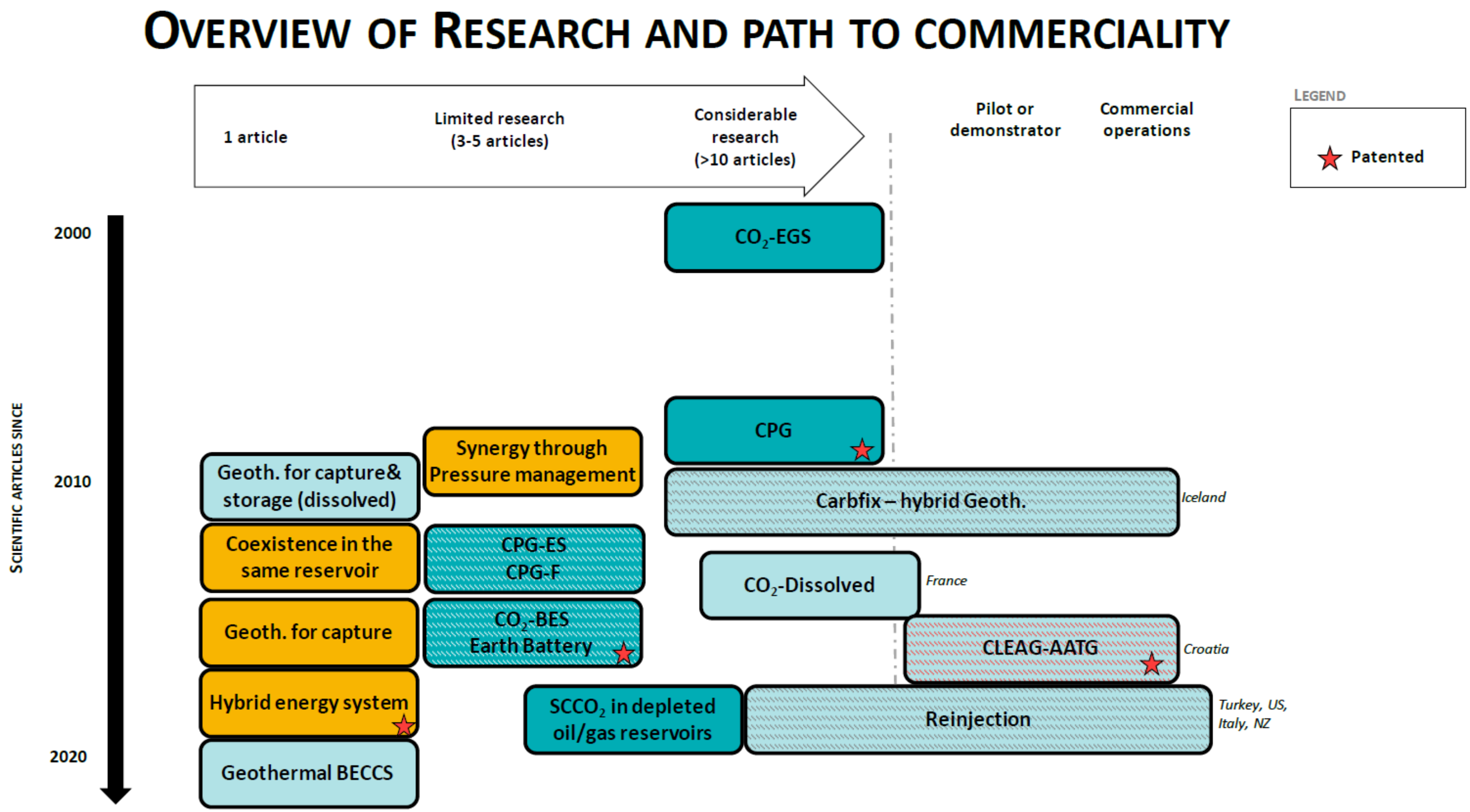


Figure 55. Overview of concepts according to readiness

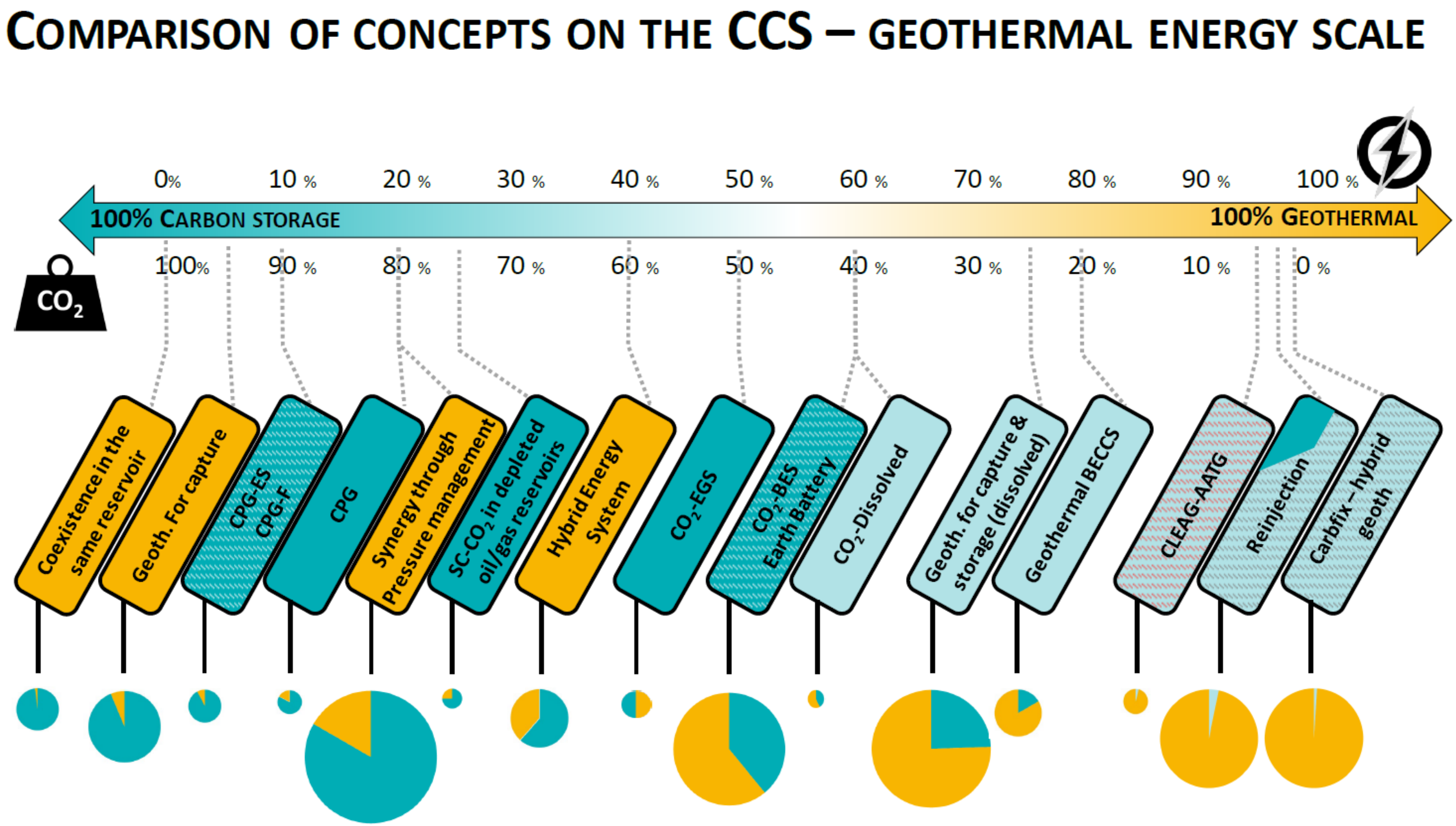


Figure 56. Overview of concepts according to the focus on CCS and geothermal exploitation, using the index of services ratio defined in section 4.4.1. The pie chart size relate to the estimate scale of the concept. Note: the pricing assumptions used to elaborate the index of services ratio has limited influence on the ordering of concepts on this chart.

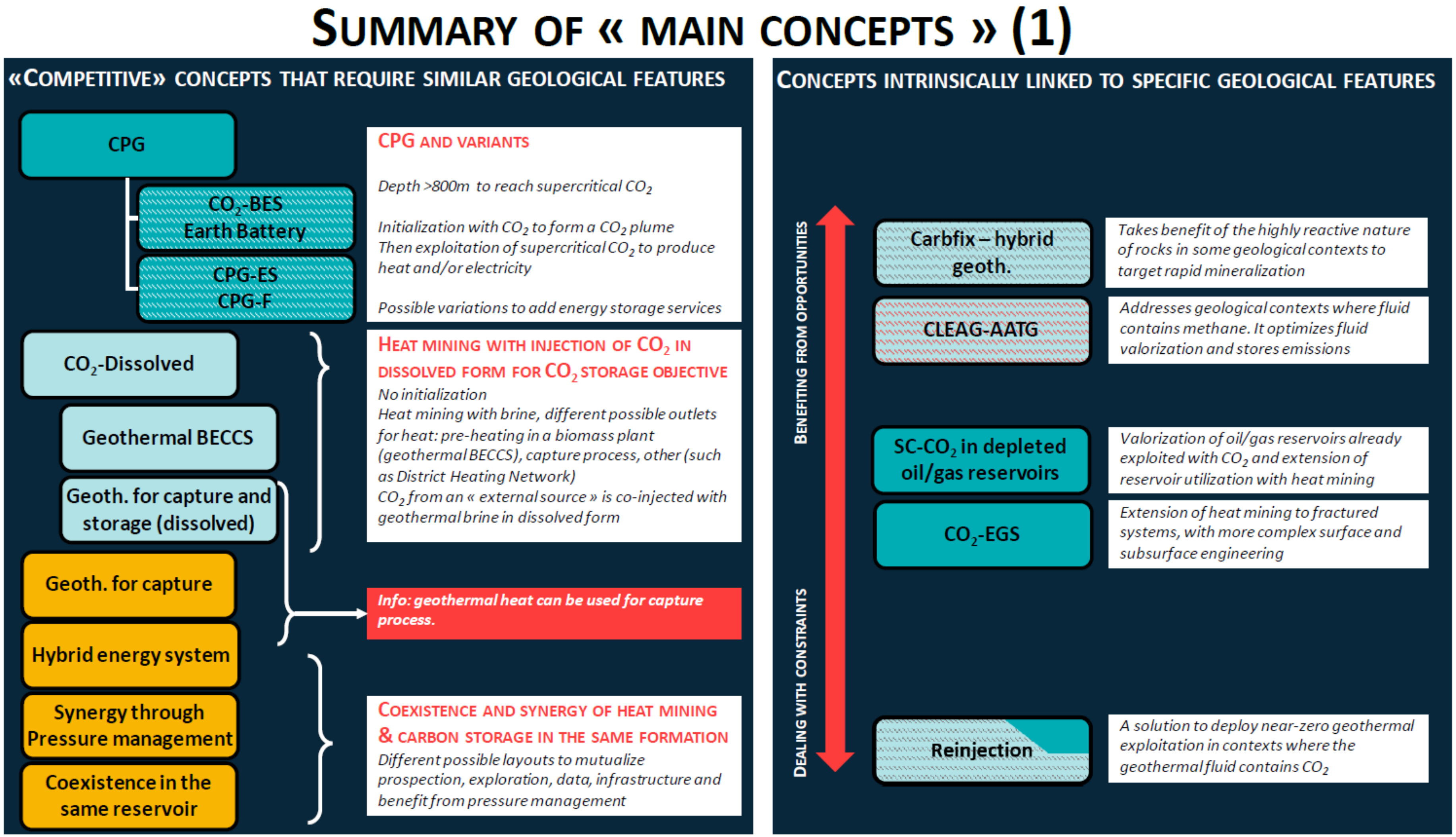


Figure 57. A summary of concepts – version 1

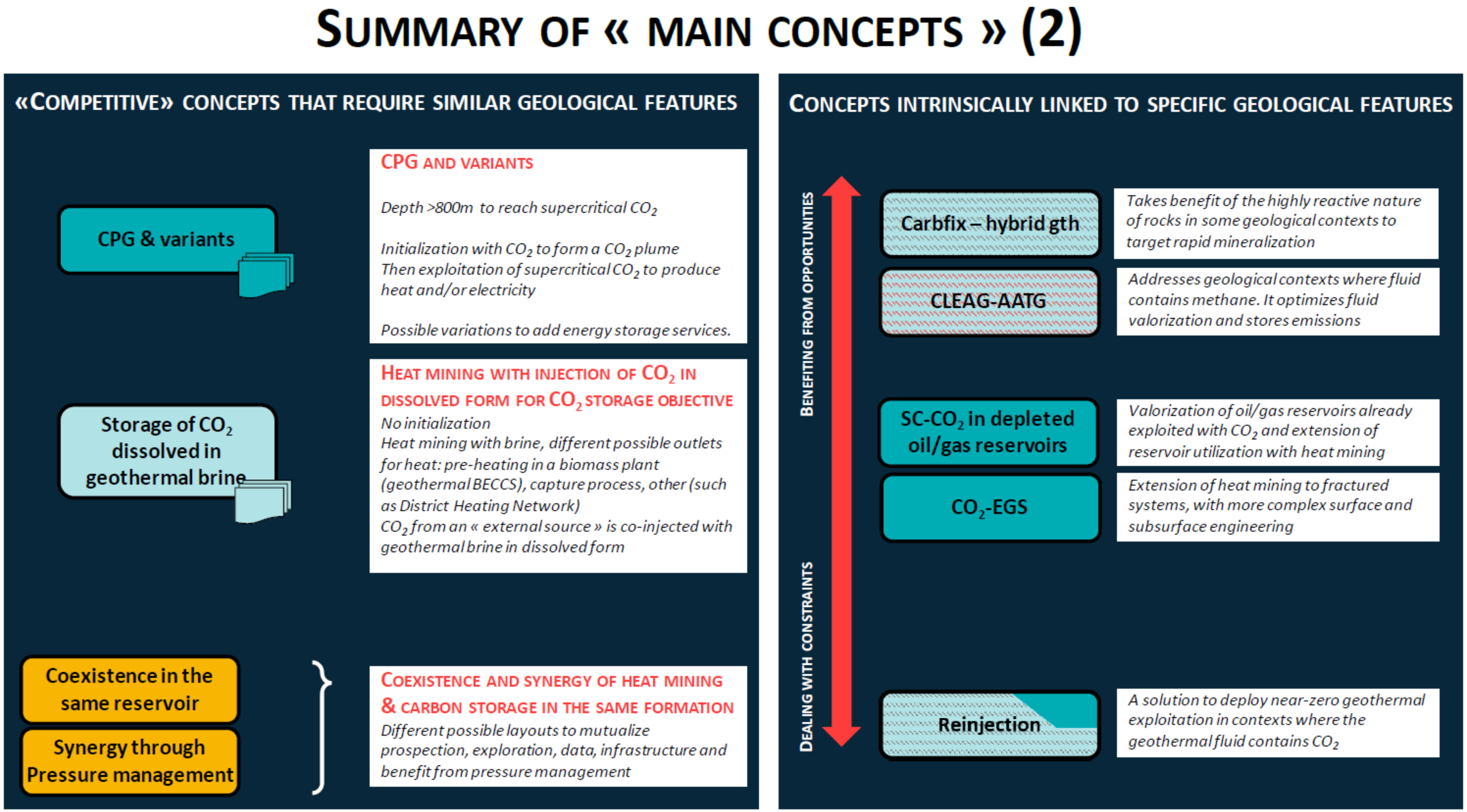


Figure 58. A summary of concepts – version 2

	AMBITIONS & REPLICABILITY	INTEGRATION, MODULARITY & SCALABILITY	PERCEPTION BY STAKEHOLDERS	READINESS	ENVIRONMENTAL RISKS & IMPACTS	TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	CREDIBLE PATH TO COMMERCIALITY
CPG	4.3	3.0	3.0	3.0	3.8	3.0	3.0
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
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
Hybrid-energy systems	3.5	4.0	3.0	2.0	3.8	3.5	3.0
CCS with geothermal energy for capture process	3.3	3.7	3.0	3.0	3.8	3.5	3.5

Figure 59. Comparison of concepts that require similar geological features

5 Assessment of potential application areas for combined CO_2-storage/geothermal projects

The applicability of the combined use of geothermal energy and CO_2 storage requires the coexistence of favourable geological conditions likely to offer a geothermal resource and demonstrating the required properties for CO_2 storage, simultaneously with a relatively close industrial CO_2 emission source or an infrastructure for transporting CO_2 from a distant emission site.

However, the matching of such criteria alone does not necessarily guarantee the feasibility of a project relying on one of the technologies presented in the previous chapters of this report. Each case is site-specific. In addition to technical and scientific questions that might be pending, especially for low-TRL concepts, other aspects also need to be considered, for example, 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)

All of these factors and more, depending on the site, need to be considered before drawing any definitive conclusions on the feasibility of a project.

The assessment of all these supplementary criteria is far beyond the scope of this study. This can only be done at a local scale for a specific hybrid concept of interest. The ambition here is to provide the reader with some methodological guidance on how these types of questions can be solved, at least partly, starting from publicly available data. The purpose here remains to establish a preliminary prefeasibility potential mapping based on technical criteria only.

A further difficulty encountered is managing the great disparity in the quality and quantity of the publicly available data across regions of the world on industrial emitters (the so-called “external sources” of CO_2 required for several concepts) and, to a lesser extent, on deep geological data. Consequently, it was not possible to produce new maps of potential at a worldwide scale in the scope of the present study. Considering these limitations, and in agreement with IEAGHG, this section focuses on exemplary case studies, mostly based on data from previous studies, to illustrate what could be achievable in a future dedicated project as and when data become available, possibly enriched by local non-public information and new data acquisition.

5.1 Subsurface data in order to identify and characterize appropriate reservoirs

Determining the geothermal resource and/or the potential capacity and adequacy of a reservoir identified in a given area for further CO_2 storage involves:

i) determination of the relevant criteria that will define the geothermal resource(s) and the CO_2 storage reservoir(s), and

ii) having access to more accurate geological data at the appropriate spatial scale.

A geothermal reservoir is defined by the presence of a heat source (heat flux, depth), a fluid, and sufficient permeability for fluid recharge (Harvey et al., 2016). For a CO_2 storage reservoir, good permeability and porosity are required, as well as the presence of an overlying impermeable caprock (in order to guarantee structural trapping and then storage security by preventing CO_2, when in gas or supercritical phase, to migrate upwards to overlying geological formations).

In order to access these criteria, three categories of data to consider are distinguished:

- Geological data, e.g. maps, field observations and sampling, borehole data (cores, logs, petrology, petro-physical properties), etc.
- Geophysical data, e.g. seismic profiles, magneto-telluric survey measurements, etc.
- Geochemical data, e.g. geo-thermometers, brine composition including NCG content (notably CO_2, if present), etc.

The expertise of geoscientists is required to analyse raw data and provide a sound interpretation of the geological context at the scale of interest for the purpose of determining whether i) a geothermal resource is available and ii) CO_2 could be stored safely. Obviously, depending on the maturity of research, the availability of data (or the possibility to acquire them) will directly govern the level of accuracy that can be reached for characterizing the area of interest.

In order to illustrate how these types of data can be integrated into a study aiming at assessing the feasibility of the combined use of the subsurface, two subsections present examples of interpreted datasets that could be used for the assessment of CCS potential and geothermal energy resources respectively.

5.1.1 *Examples of datasets for CCS*

A good example of a large-scale dataset is the atlas developed by the CarbFix team and available on the project website (https://www.carbfix.com/atlas). As indicated on the website, the objective here was to answer the question: “where does CarbFix work?” Even though the CarbFix concept is a pure CCS approach (without standard coupling with geothermal energy, except in some cases earlier described in this report), it is interesting to mention this atlas as it demonstrates where the CarbFix technology could work at a very large scale (cf. Figure 60). However, the consequence of such a large-scale investigation is that detailed information is inevitably lacking. For instance, no indication is available on the properties of the reservoirs (depth, permeability, porosity, temperature, etc.), and the actual availability of water in these reservoirs, both of which are critical features for a CarbFix system to be implemented. Consequently, it is not possible, from this sole information, to conclude on the feasibility of a future project in the presumably favourable geological areas around the world (identified in yellow on the map of Figure 60). More detailed information is necessary, which cannot reasonably be done at such large scale and requires complementary investigations at smaller scale, such as that completed by the CarbFix team for their current and under construction pilot projects.

As another interesting example of worldwide dataset, one can refer to the OGCI’s CO_2 storage catalogue map (Figure 61) which is an independent worldwide evaluation of geological CO_2 storage resource assessments. It assesses CO_2 storage resource sites from the perspective of commercial viability and readiness, as well as technical opportunity. This is more directly oriented toward standard CCS applications, but it is also of interest when combined with geothermal potential maps, for preselecting first large geographical areas of interest (or, conversely, eliminating inappropriate areas) in the perspective of a future coupled CCS and geothermal operation.

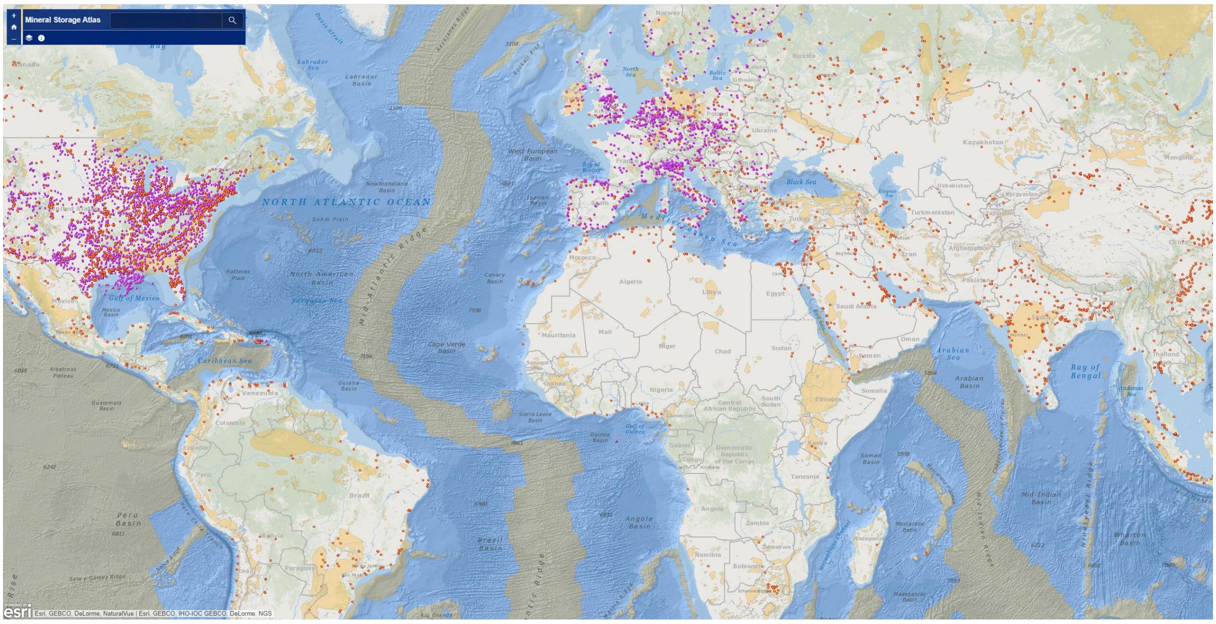


Figure 60. CarbFix atlas enabling worldwide visualization of geological areas (in yellow) with the presence of basaltic and/or ultramafic rocks favourable for the CarbFix CCS technology. Purple circles show main industrial CO_2 emitters for countries where data are available (https://www.carbfix.com/atlas).

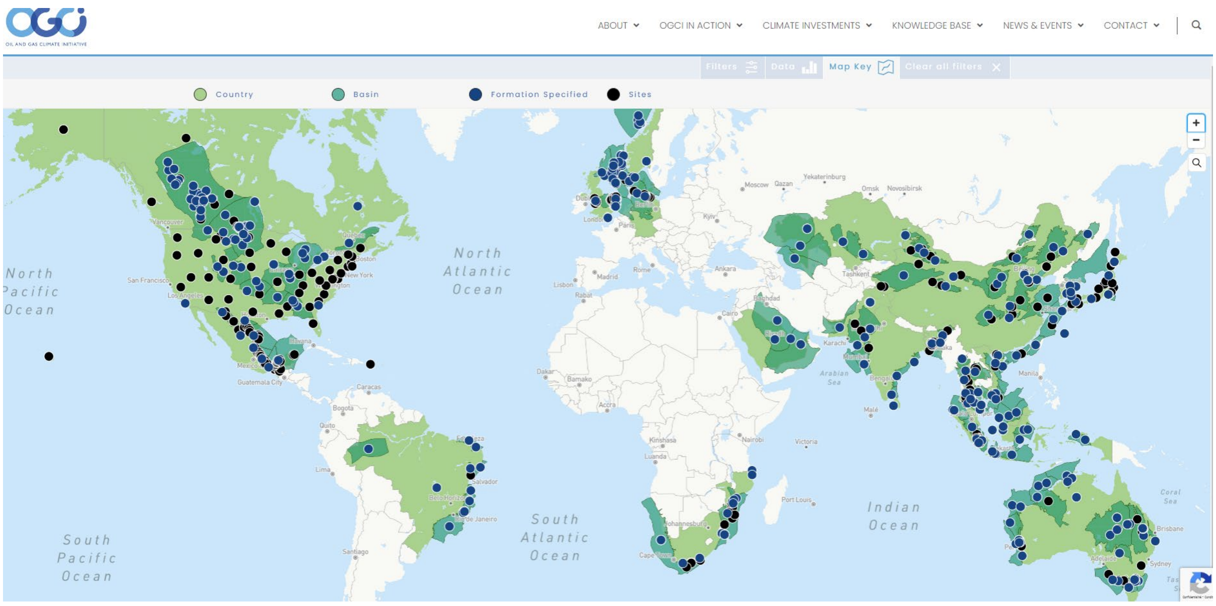


Figure 61. Map of potential CO_2 storage sites form the OGCI's CO_2 storage catalogue map (https://www.ogci.com/co2-storage-resource-catalogue/#). From this 2021 map, total storage resource was assessed to be 12,958 Gt, from 715 sites across 18 countries.

Interestingly, we can refer to other projects that aim at assessing CCS potential over specific regions of the world, thus likely to provide more accurate and detailed information.

In Australia, Geoscience Australia has made available data produced within several geological storage studies from 1999 to present. As an illustration, the map of Figure 62 gives an overview of Australia's CO_2 storage potential in the main sedimentary basins. The high-level assessment took into consideration geological characteristics and other factors in order to determine the potential, capacity and ranking of sedimentary basins for CO_2 geological storage. More detailed information is accessible through the Geoscience Australia online data portal.

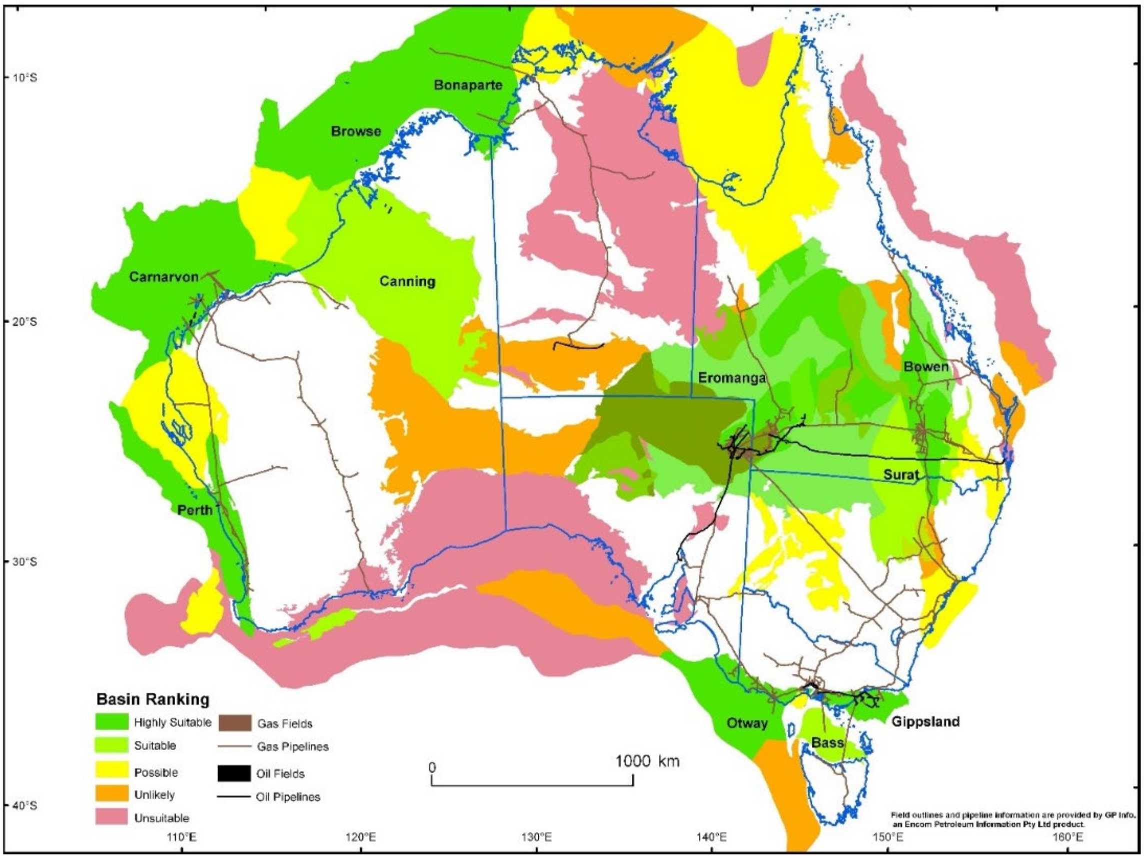


Figure 62. Australia's basins ranked for CO_2 storage potential (Carbon Storage Taskforce, 2009)

At the United States scale, one can refer to the extensive assessment work carried out by the US Department of Energy (DOE) National Energy Technology Laboratory (NETL) to produce the Carbon Storage Atlas. The primary purpose of this Atlas is to provide a coordinated update of CCS potential across the United States and other portions of North America. The fifth edition (Atlas V), published in August 2015, contains updates to the CO_2 storage potential for the United States and updated information on DOE's carbon storage activities and field projects. Atlas V includes current and best available estimates of potential CO_2 storage resource determined by a methodology applied across all of the regions. Carbon dioxide storage resource estimates were derived from data collected by DOE field projects. An example of a map for saline aquifer formations is shown in Figure 63.

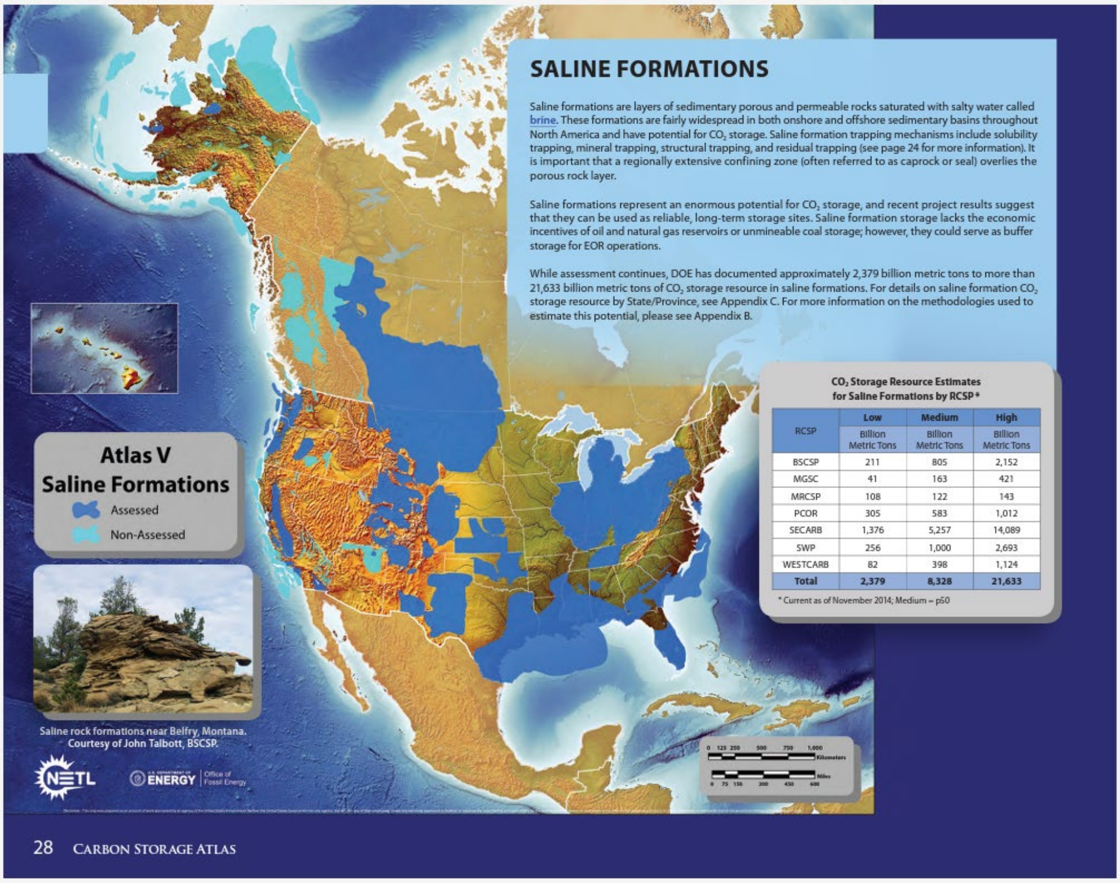


Figure 63. Map from the US DOE's Carbon Storage Atlas (fifth edition) showing the North American saline formations identified as suitable for CO_2 storage, and their respective CO_2 storage resource estimates.

At the European scale, the report recently published by the Geological Survey of Denmark and Greenland (Anthonsen and Christensen, 2021) gives a summary of some key results on CO_2 storage capacities in Europe (both onshore and offshore) established from data of the EU-funded project CO_2STOP (https://energy.ec.europa.eu/assessment-co2-storage-potential-europe-co2stop_en). This report delivers several interesting maps, including on showing the main European saline aquifers and their potential storage capacity, as estimated in the CO_2STOP project (Figure 64).

The European project Strategy CCUS (2019-2022 https://www.strategyccus.eu/about-project), funded by the EU's Horizon 2020 programme, aims at supporting the development of low-carbon energy and industry in Southern and Eastern Europe. For that purpose, CCUS is considered as a very promising solution as it will deliver significant cuts in emissions from the industrial and power sectors. The project focuses on eight regions identified as promising for CCUS development. As an illustration of the interactive maps produced, Figure 65 shows several potential CO_2 storage units to consider in three deep saline aquifers of the Northern Croatia region. Data on emitters are also represented on the same map, so that local stakeholders can consider what could be the best possibilities for each of them to abate their carbon footprint by targeting the most appropriate storage unit.

The ensuing project PilotStrategy (2021-2026 https://pilotstrategy.eu/), awarded by the EU's Horizon 2020 programme, also aims at investigating geological CO_2 storage sites in industrial regions of Southern and Eastern Europe to support development of large-scale CCS. This project builds on the research carried out in the Strategy CCUS project, and looks in greater detail at five regions (of the eight studied in Strategy CCUS). Research focuses on geology and numerical modelling of deep saline aquifers–porous rock formations, but also seeks to identify the best clusters of industrial emitters and engages with citizens and stakeholders. This approach perfectly illustrates the methodology one should apply in assessing the feasibility of combined use of the subsurface for geothermal exploitation and CCS.

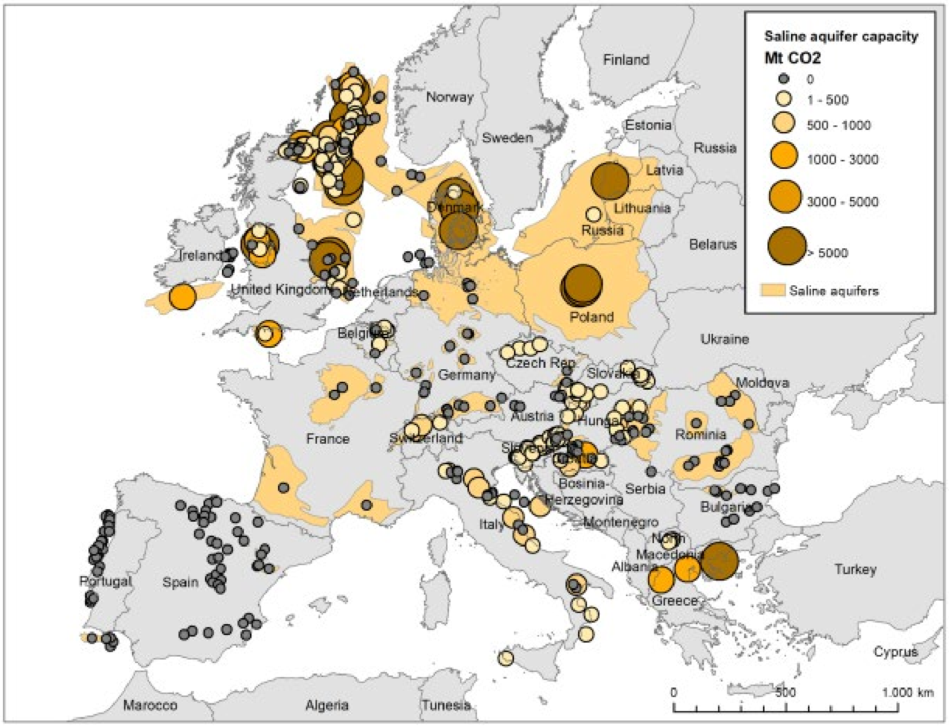


Figure 64. Location and outline of the main European saline aquifers and storage capacity (illustrated as graduated symbols) https://cdn.catf.us/wp-content/uploads/2021/10/20183953/EU-CO2-storage-summary_GEUS-report-2021-34_Oct2021.pdf

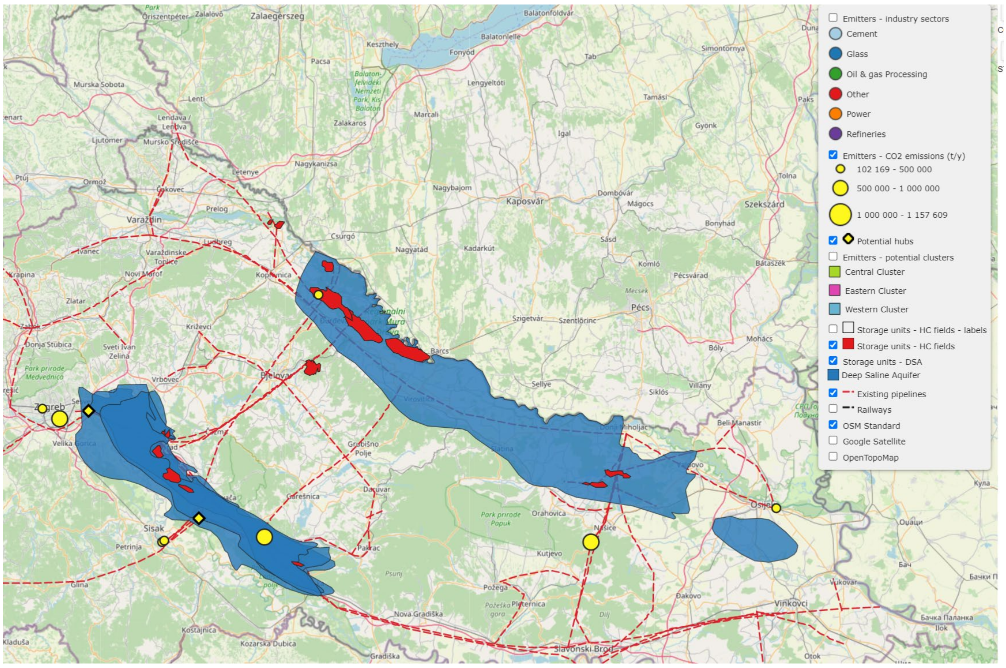


Figure 65. Interactive map for the Northern Croatia region available on the Strategy CCUS project website (https://strategyccus.eu/project-outputs/web-maps/mapping-potential-wp2), including potential storage units, saline aquifer formations, CO_2 emissions of industrial sites, and existing infrastructure (pipelines).

5.1.2 *Examples of datasets for geothermal energy*

Much information on geothermal resources, potential and installations is available in the literature and as web services at various scales (from world to city). In this section, we aim to illustrate the type of data that can be found through a few examples at world scale, continental scale, and country/state/region scale.

5.1.2.1 World scale

Assessed geothermal resources maps at the world scale are available in various publications such as Limberger et al. (2018) and Coro & Trumpy (2020). As illustrated in Figure 66 and Figure 67, these publications propose maps providing a worldwide overview of the more appropriate regions for potentially offering geothermal resources. The quality of these maps is of course very much dependent on the quality of the raw data used for computations. The heterogeneity of such data quality, according to the region of the world considered, might well induce some bias in the computation results and consequently the maps. However, such maps are interesting for an initial preliminary analysis and subsequently need to be refined at lower scales for actual exploitation, with the aim of determining the feasibility of exploiting geothermal energy in a "local" geological formation.

The International Geothermal Association (IGA) gives regular updates of the geothermal power use for each country, based on the country updates presented every five years at the World Geothermal Congress. A synthetic database is available on the IGA website (https://www.lovegeothermal.org/explore/our-databases/geothermal-power-database/) including a global map (Figure 68). The database includes, for each country, thermal and electric power, as well as energy produced from 1995 to 2015. Sweden is the largest producer of geothermal heat, mainly from shallow geothermal sources. For electricity and therefore for deep geothermal exploitation, the USA is the world's top-producer with 3,500 MWe. New Zealand, Mexico, Indonesia, Philippines, Italy, Iceland, Kenya and Japan produce more than 500 MWe each and are the largest producers of geothermal electricity behind the USA.
For more detailed information, the reader may refer to the webmap of Think Geoenergy, a website of geothermal news, which gives the location of power plants as well as their installed capacity and technology used (https://www.thinkgeoenergy.com/map/).

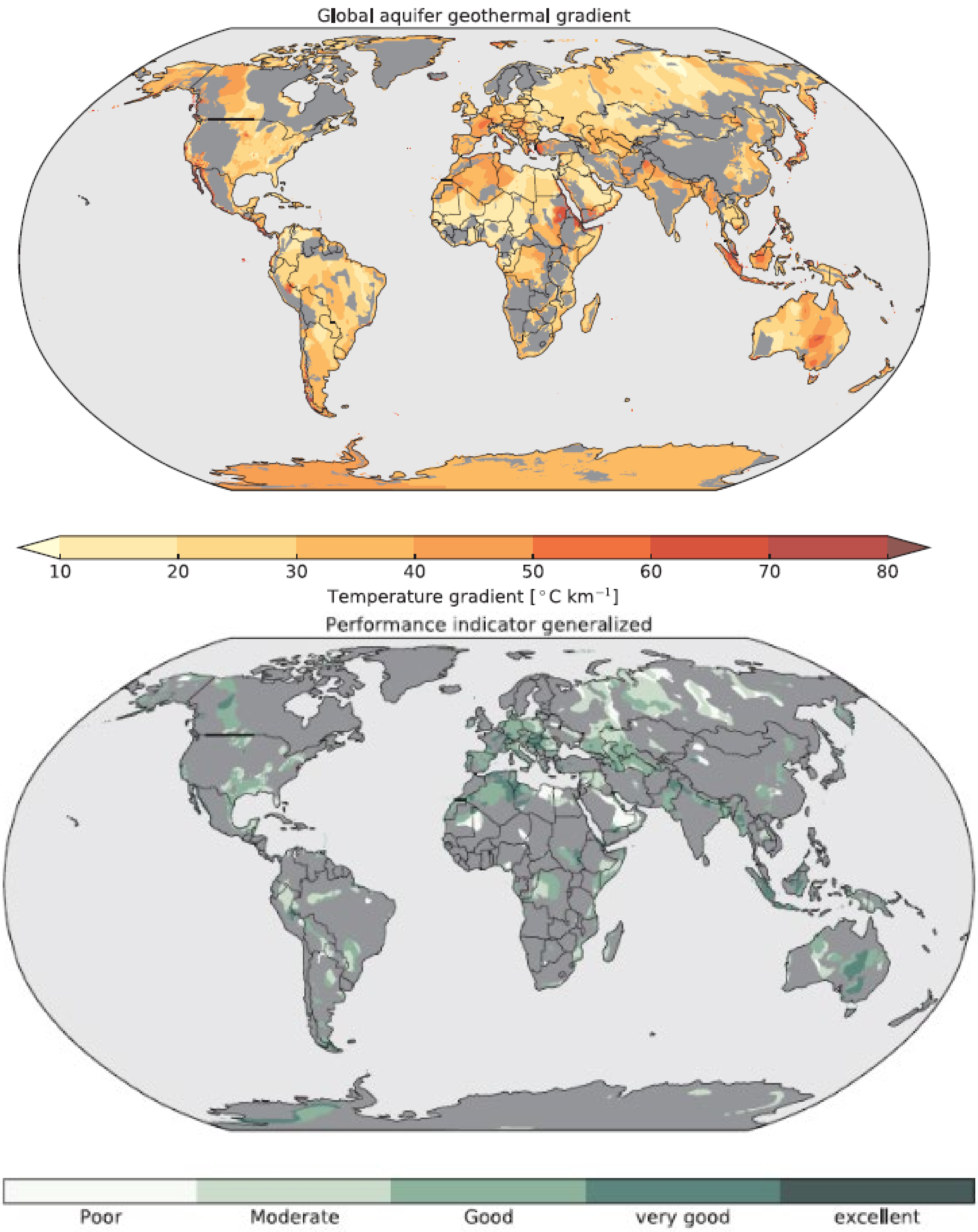


Figure 66. Assessed worldwide geothermal resources from computed data on temperature gradient (top) and performance indicator for low-enthalpy direct heat application (bottom) (Limberger et al., 2018)**.**

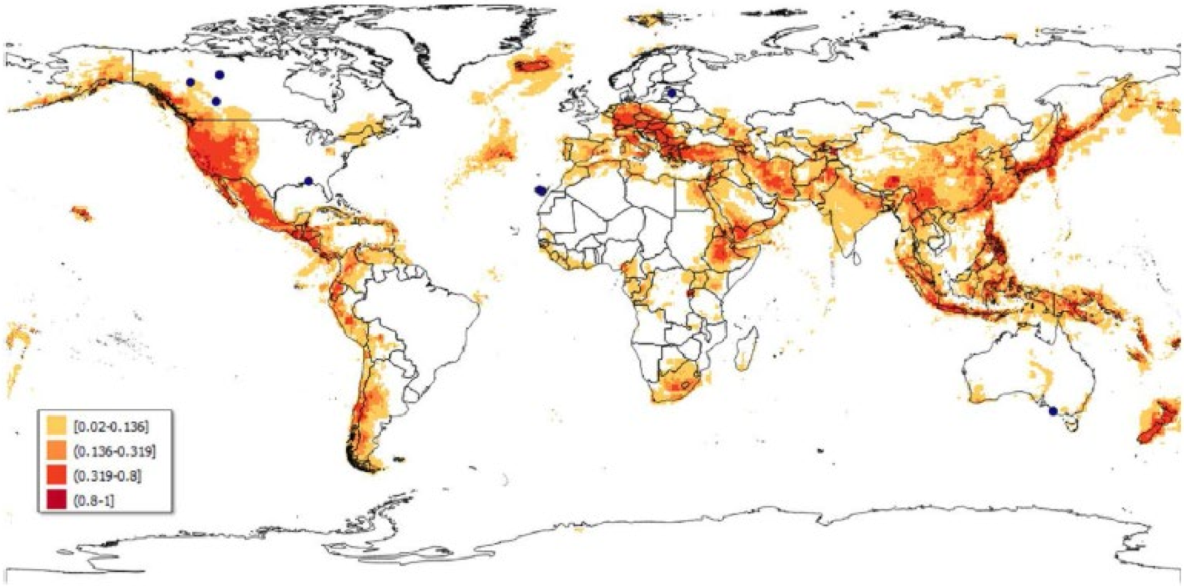


Figure 67. Computed geographical suitability of geothermal power plants at the world scale (Coro and Trumpy, 2020)**.**

Figure 68. Global Geothermal Use 2015 based on the IGA database (https://www.lovegeothermal.org/explore/our-databases/geothermal-power-database/)

5.1.2.2 Continental scale

At a lower spatial scale, a higher accuracy and completeness of data is achievable. As an illustration, Figure 69 shows a map displaying both geological (location of reservoirs), geophysical (heat flow density and temperature distribution at depth), and surface infrastructure (existence of geothermal district heating networks). This map, and also references to detailed information on geothermal energy use for district heating (notably GEODH, 2014), are available from the information hub about Geothermal District Heating in Europe (GeoDH.eu: http://geodh.eu/).

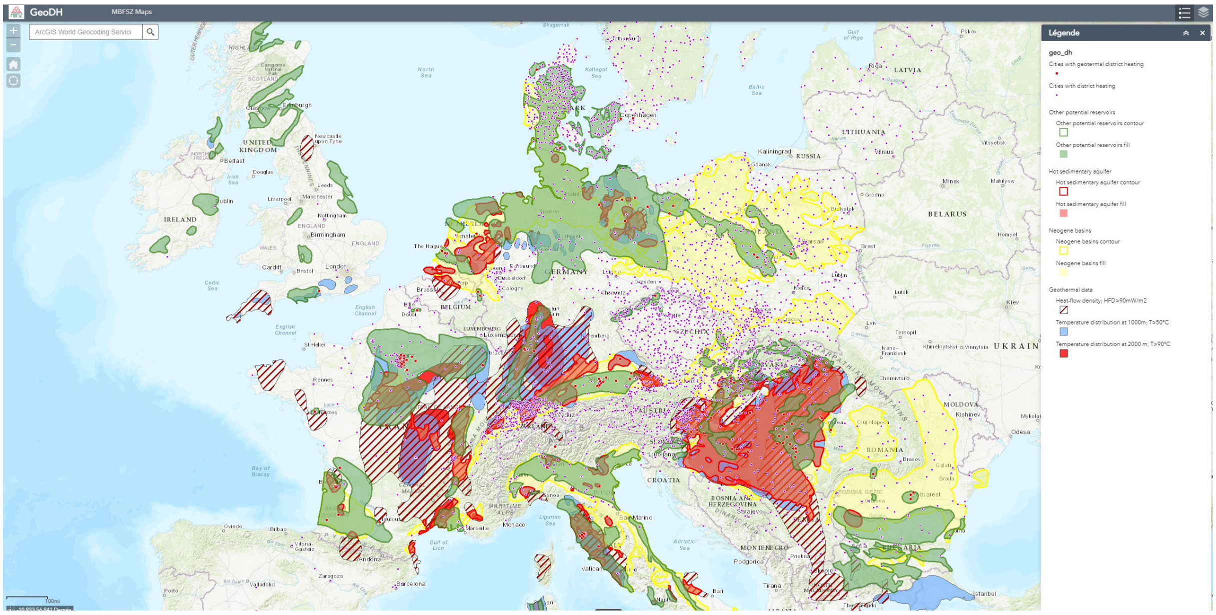


Figure 69. Map showing favourable regions for geothermal district heating in several European countries. This map is available on the information hub about Geothermal District Heating in Europe (GeoDH.eu) website (https://map.mbfsz.gov.hu/geo_DH/).

For Africa, some databases and large-scale geothermal potential maps exist, but are not directly available on the web. In the framework of the European program LEAP-RE (https://www.leap-re.eu/), a database of geothermal resources and associated GIS online (Geothermal Atlas for Africa) is under construction and aims to define the origin and location of low- to high-enthalpy geothermal resources for the development of African electricity production, plus a range of direct heat/cold use applications and water use (Figure 70).

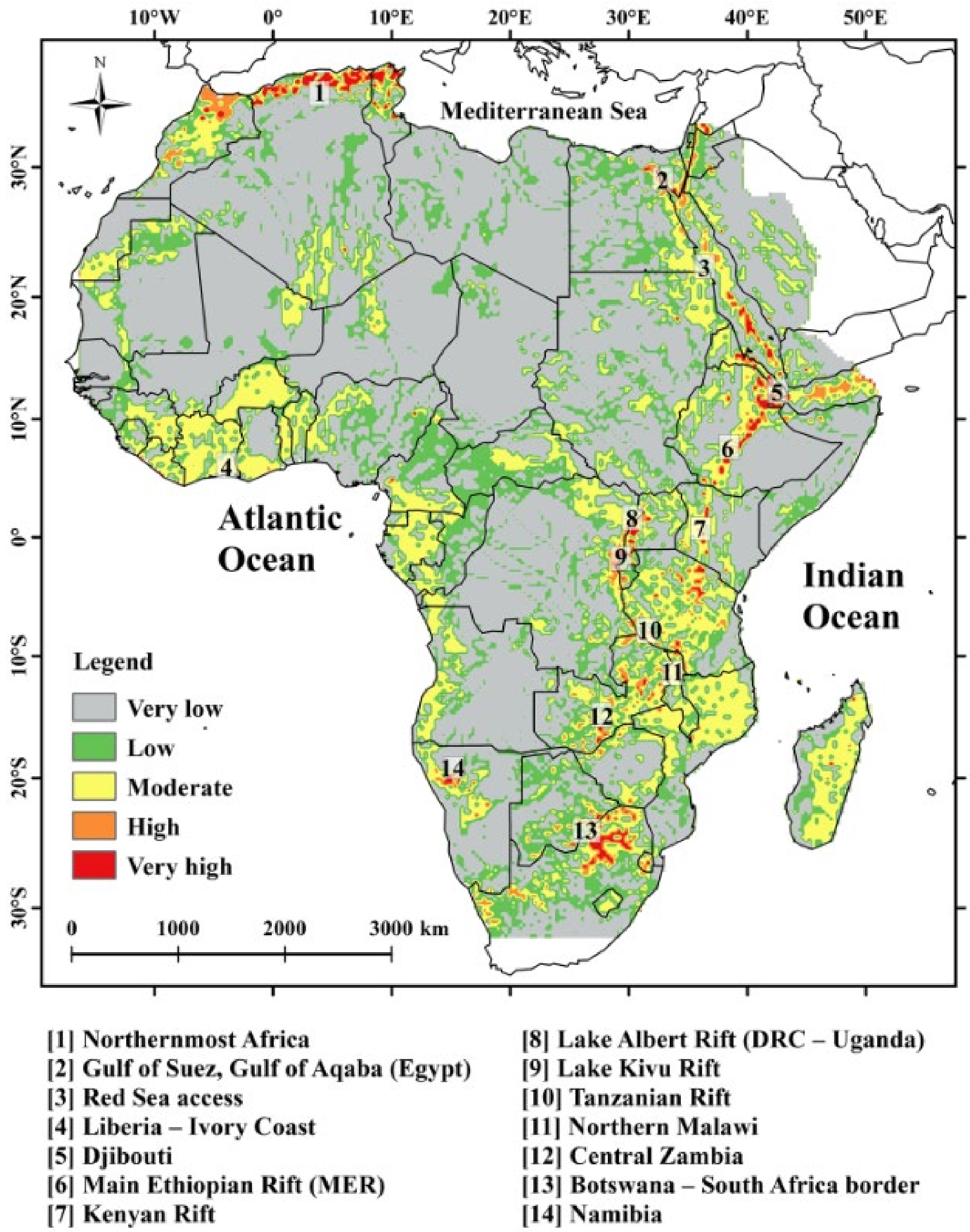


Figure 70. Geothermal potential map of Africa identifying 14 areas with high geothermal potential that might be exploited for more geothermal investigation and development (Elbarbary et al., 2022)

5.1.2.3 Country/state/region scale

Several countries offer a web service providing data and maps accessible to the public, policy makers and companies. Generally, key information given by these websites is related to the resource formation (depth, thickness), the temperature at various depths, and surface installations. For example, in France, the Géothermies website (https://www.geothermies.fr/viewer/) provides information for the main basins and the deep (>200m) and shallow (<200m) geothermal installations (Figure 71).

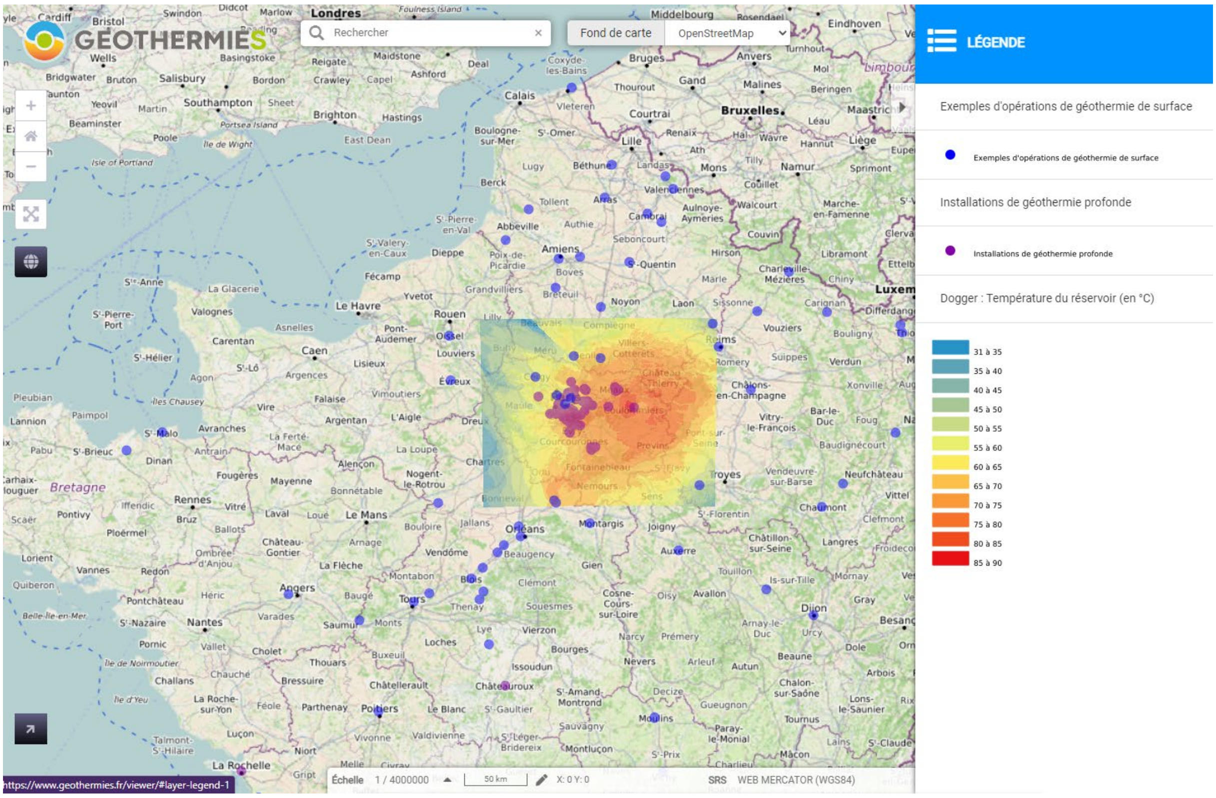


Figure 71. Temperature map at the top of the Dogger reservoir in the French Paris Basin, and the shallow (blue circles) and deep (purple circles) geothermal installations (https://www.geothermies.fr/viewer/).

Other websites propose more detailed information, such as details on existing geothermal facilities, geothermal potential of identified aquifers, and other general data of interest (e.g. energy consumption and population density, etc.). This is the case of GeotIS, the German online Geothermal Information System https://www.geotis.de/geotisapp/geotis.php), which enables the display of combinations of data about geothermal facilities of all types (from spa to district heating and electricity generation), geothermal potential (temperature, reservoir hydraulic conductivity), population's energy consumption and density (useful for assessing matching between energy production potential and local energy needs. Interestingly, GeotIS also gives access to maps of areas worthy of examination for CO_2 storage (Figure 72), making this tool particularly useful for determining potentially favourable areas for implementing a combined CCS-geothermal project.

For The Netherlands, the ThermoGIS website (https://www.thermogis.nl/en/map-viewer) goes further and enables the display of various types of potential (economic, technical, power, recoverable heat, heat in place, etc.) and the calculation of the expected productivity of a doublet with the DoubletCalc1D model developed by TNO (Figure 73).

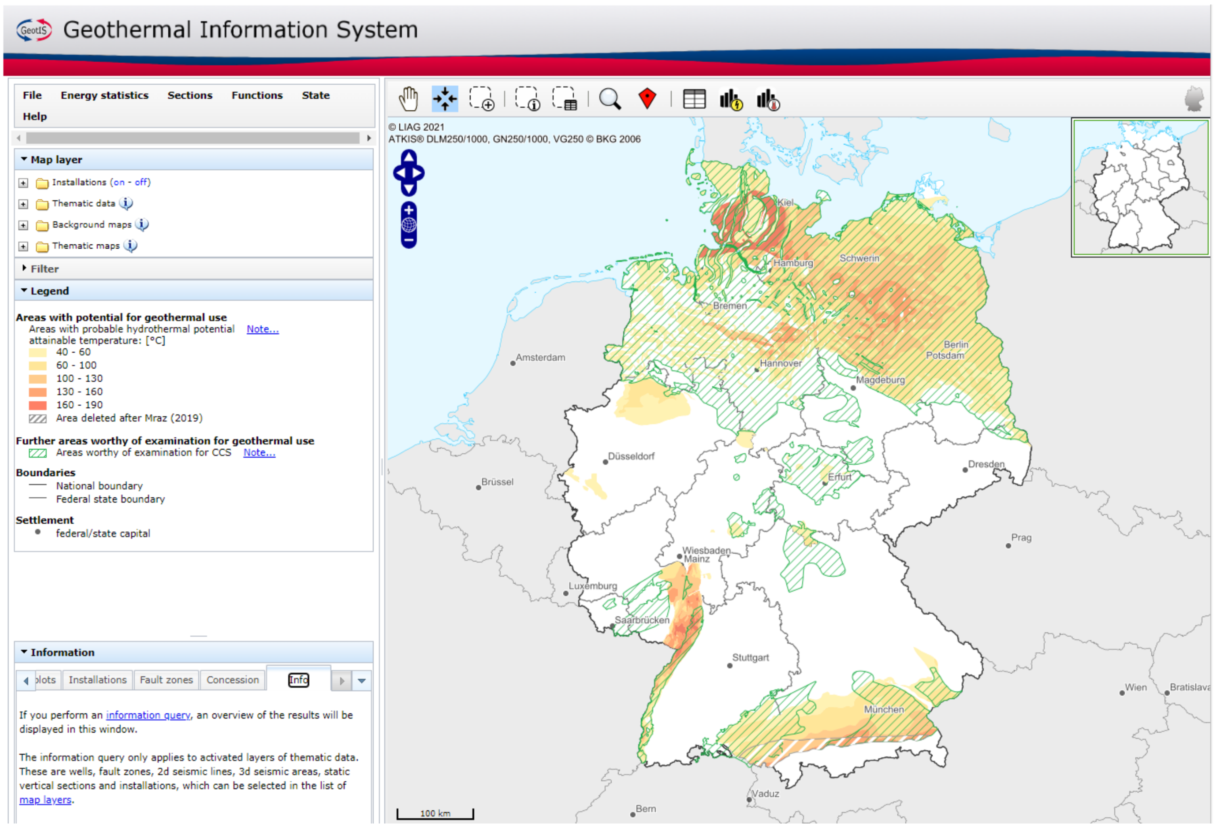


Figure 72. Map of indicated hydrothermal potential and areas worthy of examination for CO_2 storage in Germany (https://www.geotis.de/geotisapp/geotis.php).

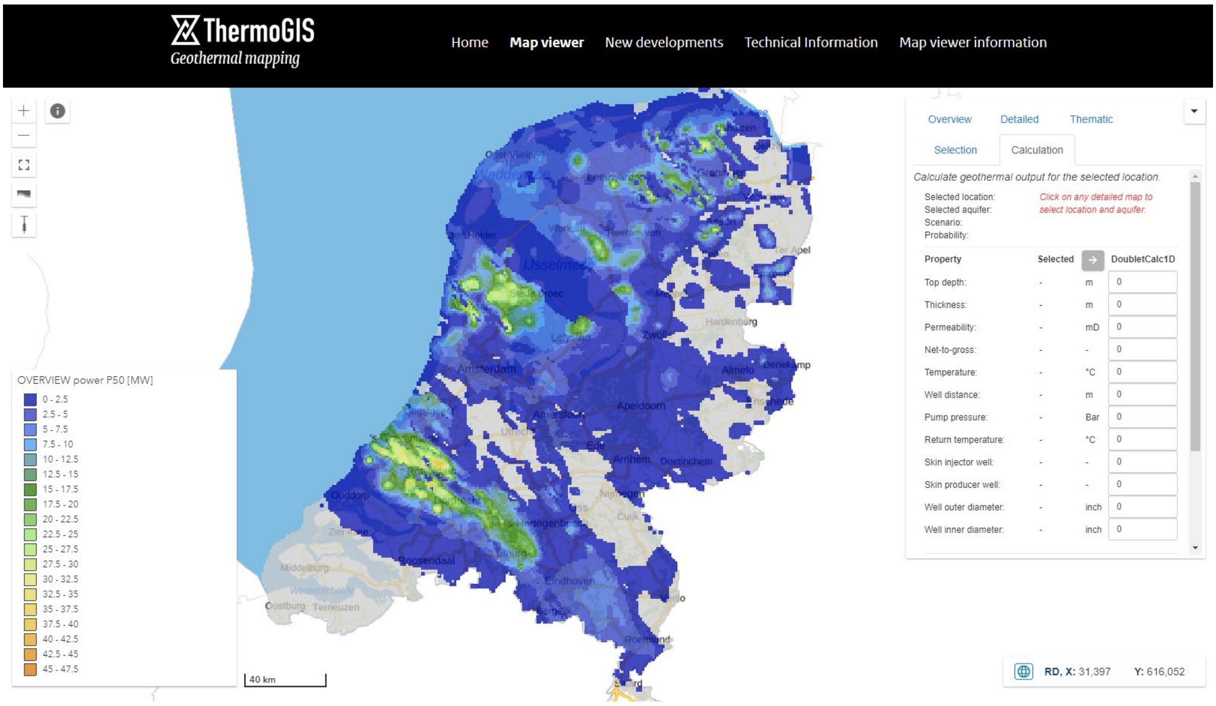


Figure 73. ThermoGIS website: geothermal power map for The Netherlands and, on the right, overview of the interface of the TNO's DoubletCalc1D computation module enabling calculation of the expected productivity of a doublet (https://www.thermogis.nl/en/map-viewer).

For a sound assessment of the feasibility of a geothermal project, however, decreasing the spatial scale is mandatory. Regional scale seems appropriate for such an objective. As an example, the Interreg IV Project GeORG (https://www.geopotenziale.org/home?lang=2) explores the geological potential of the deep Upper Rhine Graben, both for estimating geothermal resources and gas-storage potential (including CO_2). GeORG have provided a whole Upper Rhine Graben 3D geological model including detailed information on geological formations and features. The results are available through an interactive map viewer (https://maps.geopotenziale.eu/?app=georg&lang=en, Figure 74). The shape files of position and thickness of various horizons, temperature, heat in place, CO_2 storage potential are also available on request, offering interesting perspectives to further assess the implementation feasibility of a combined geothermal/CCS project in this specific sector.

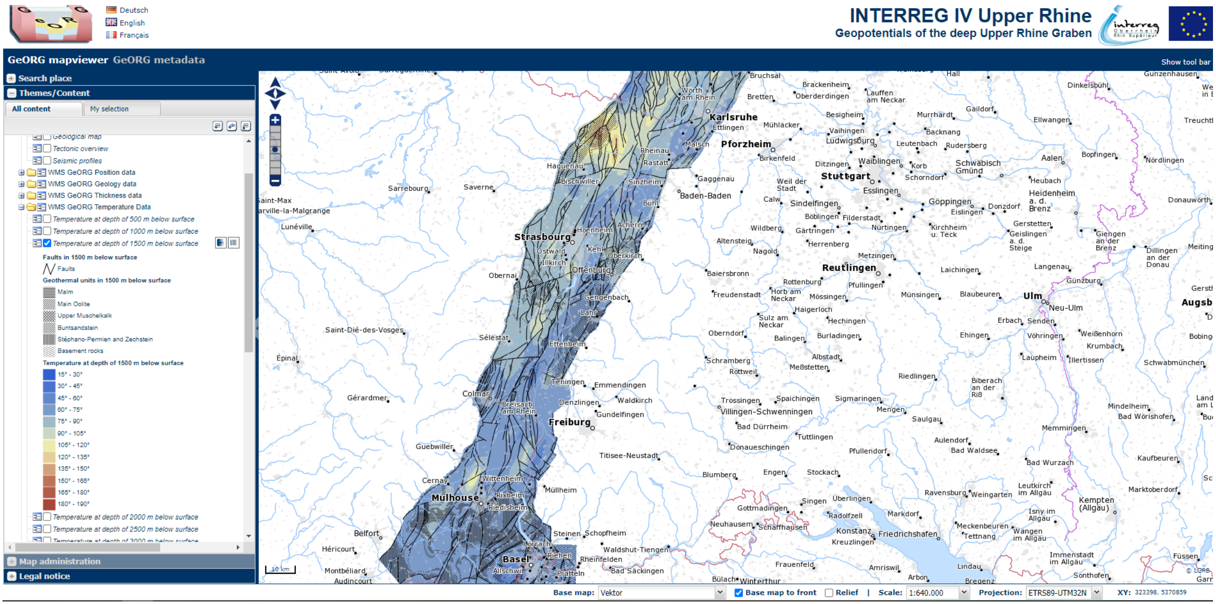


Figure 74. A map produced using the interactive web service of the GeORG project (https://maps.geopotenziale.eu/?app=georg&lang=en). Here, temperatures at a depth of 1,500 m below surface are displayed.

In the USA, the National Renewable Energy Laboratory (NREL) makes available geothermal resource data, tools and maps that are all downloadable as image or shape format (https://www.nrel.gov/gis/geothermal.html, Figure 75). The maps are not presented through a map viewer, but many datasets are available and useable directly though any GIS. Therefore, this is not intended for the public or policy makers, but is very useful for engineers and researchers to produce cross-mapping and cross-analysis. The US Department of Energy (DOE) hosts a Geothermal Data Repository (GDR) to collect data from researchers and to make them available (https://gdr.openei.org/home). These data come from all projects funded by the US DOE's Geothermal Technologies Office, like the FORGE Project, the EGS Collab Project and the Geothermal Play Fairway Analysis Project (for more information see the abovementioned GDR website).

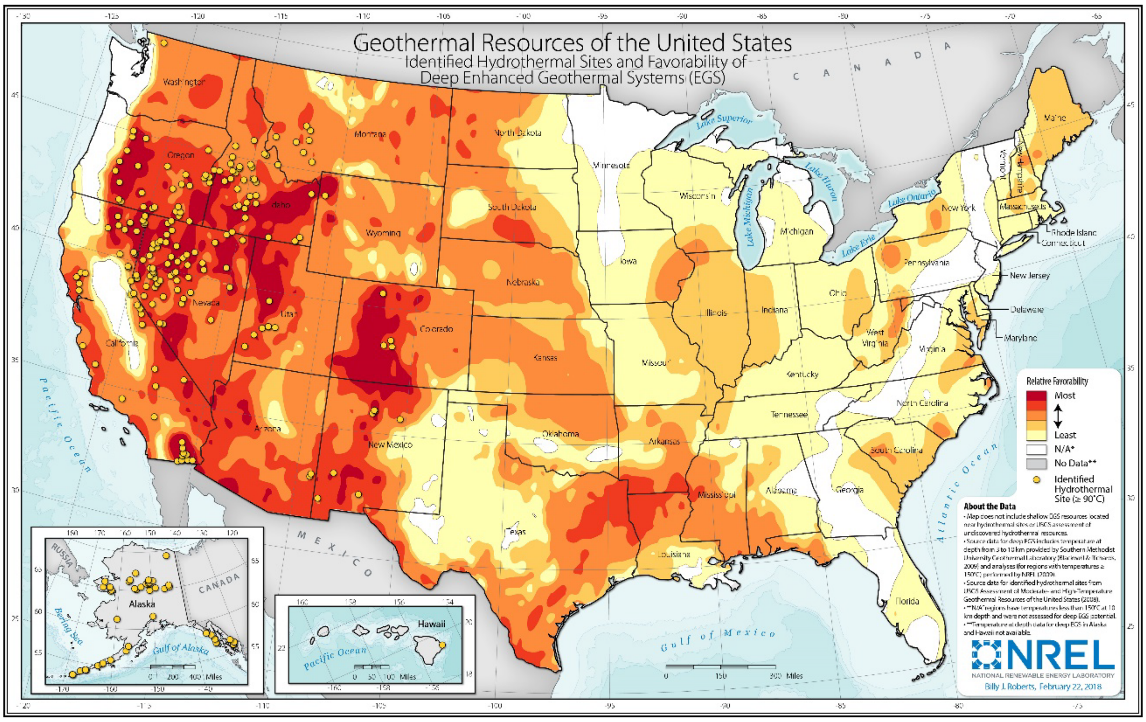


Figure 75. Geothermal Resources of the United States: Identified Hydrothermal Sites and Favourability of Deep Enhanced Geothermal Systems (https://www.nrel.gov/gis/assets/images/geothermal-identified-hydrothermal-and-egs.jpg).

The NREL and the US Agency for International Development own the Renewable Energy Explorer website, which provides information about technologies and analysis features for various developing countries (https://www.re-explorer.org/launch.html). From this website, the location and some information about geothermal installations for Afghanistan, Kenya, Mexico and Pakistan are available through a map viewer (https://www.re-explorer.org/re-data-explorer/). However, little information is associated to the installation, except temperature (see the example of Afghanistan in Figure 76).

As an example of data at the province/territory scale, we can refer to the Canadian Geothermal Association (CanGEA, https://www.cangea.ca/maps.html) that provides maps and reports, particularly for the western part of Canada: Alberta, British Columbia, Yukon, and Nunavut. Like the NREL website for the USA, no map viewer is directly available here, but various types of images and “kmz” files (Google Earth viewable files) can be downloaded (Figure 77). Details and explanations for the maps can be found in the downloadable public reports.

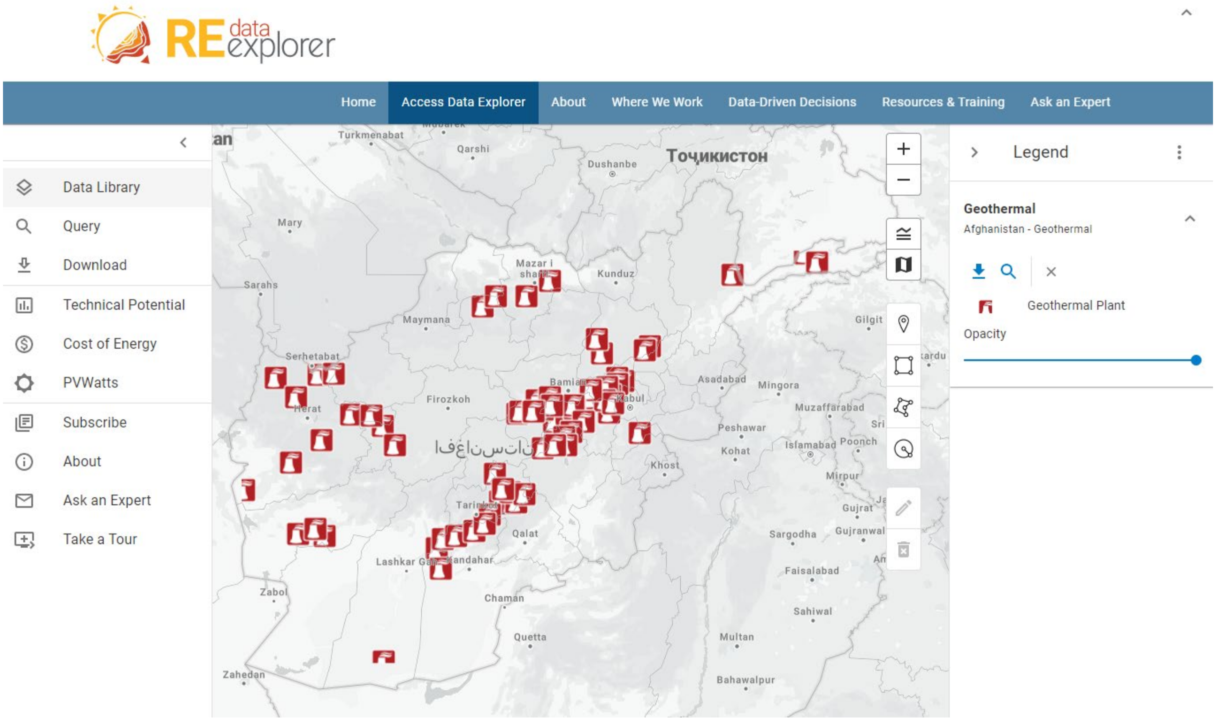


Figure 76. Location of geothermal plants in Afghanistan (https://www.re-explorer.org/re-data-explorer/).

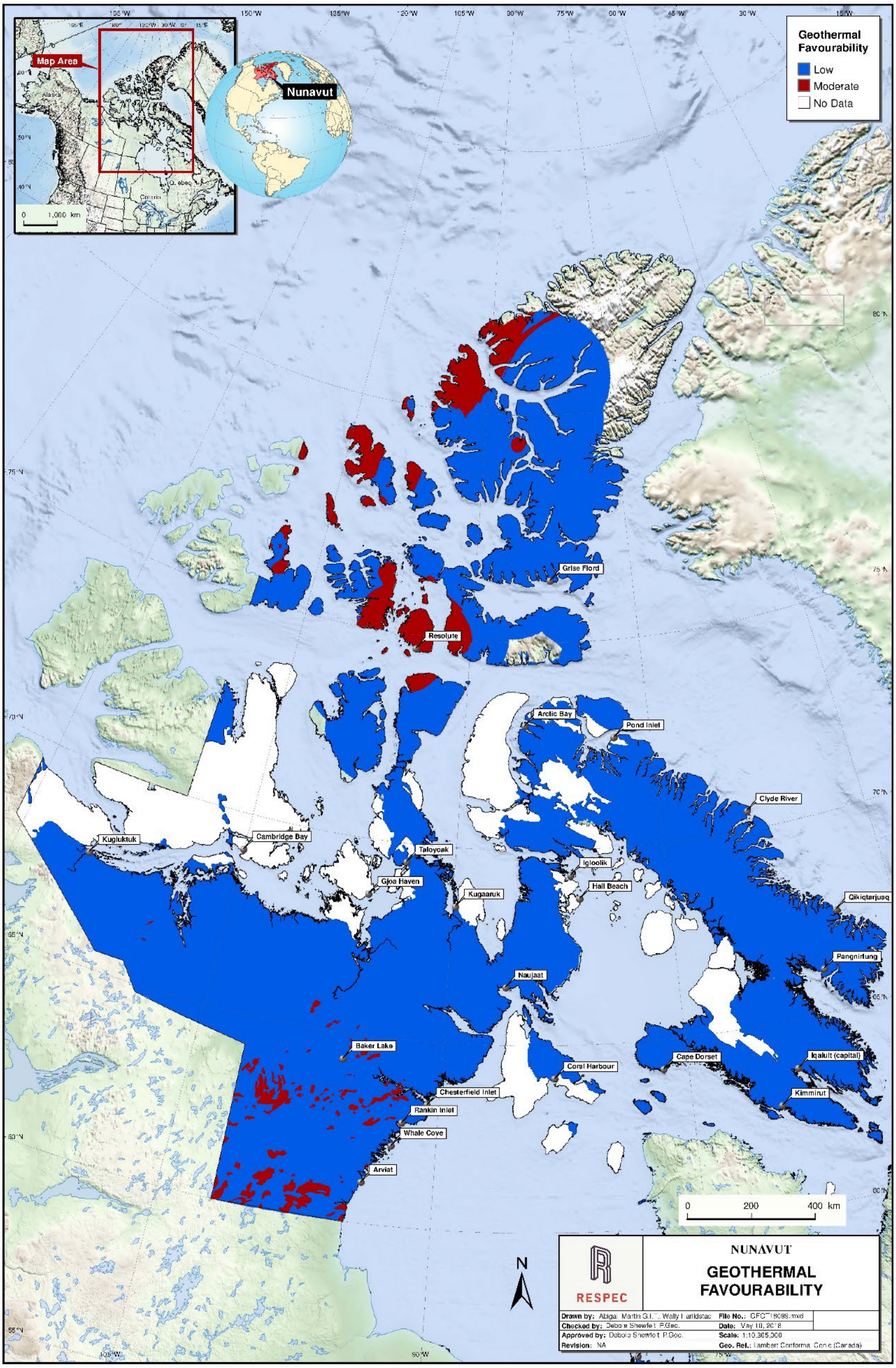


Figure 77. Geothermal favourability map for Nunavut, Canada (https://www.cangea.ca/nunavutgeothermal.html).

5.2 Data on industrial CO_2 emissions

For all the concepts requiring an external source of CO_2, the matching between favourable subsurface conditions and the proximity of one or several industrial CO_2 emitters is a prerequisite for determining the potential applicability in an area of interest. Geolocalized data on the industrial sites emitting CO_2 are needed.

The availability and the quality of such data is the central question. Depending on the country/region, the publicly available data vary considerably and, in some cases, are non-existent. Direct contact with a group of industrial operators, necessarily at a local scale, might be the only way to obtain data on CO_2 emissions in some cases. As an illustration of this data heterogeneity issue, we propose three types of datasets according to scale: world, continental and national (country/state/region).

5.2.1 *World scale*

Global data generally offer a poor level of detail. An interesting source for such data is the Global Carbon Atlas (Figure 78). Information for many countries (but not all) is provided as a total amount of emitted CO_2 per year due to fossil fuel consumption, including transport, which is not a valid source of CO_2 for the concepts considered in this study.

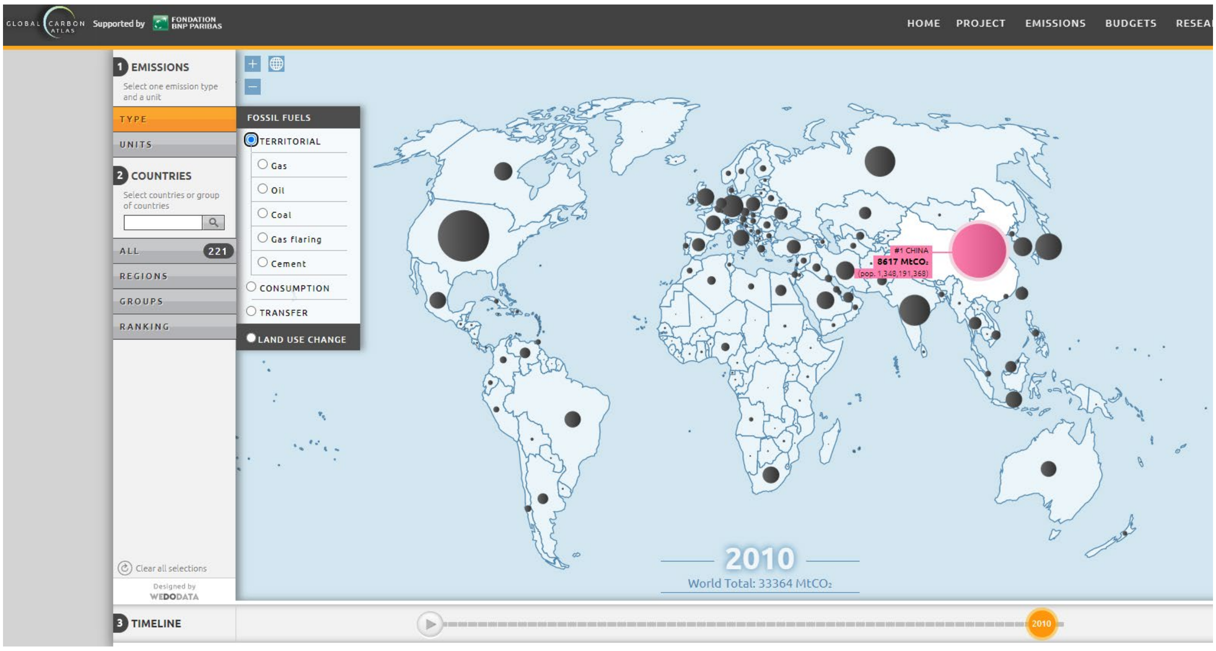


Figure 78. CO_2 emission data per country available at worldwide scale in the Global Carbon Atlas (http://www.globalcarbonatlas.org/en/CO2-emissions).

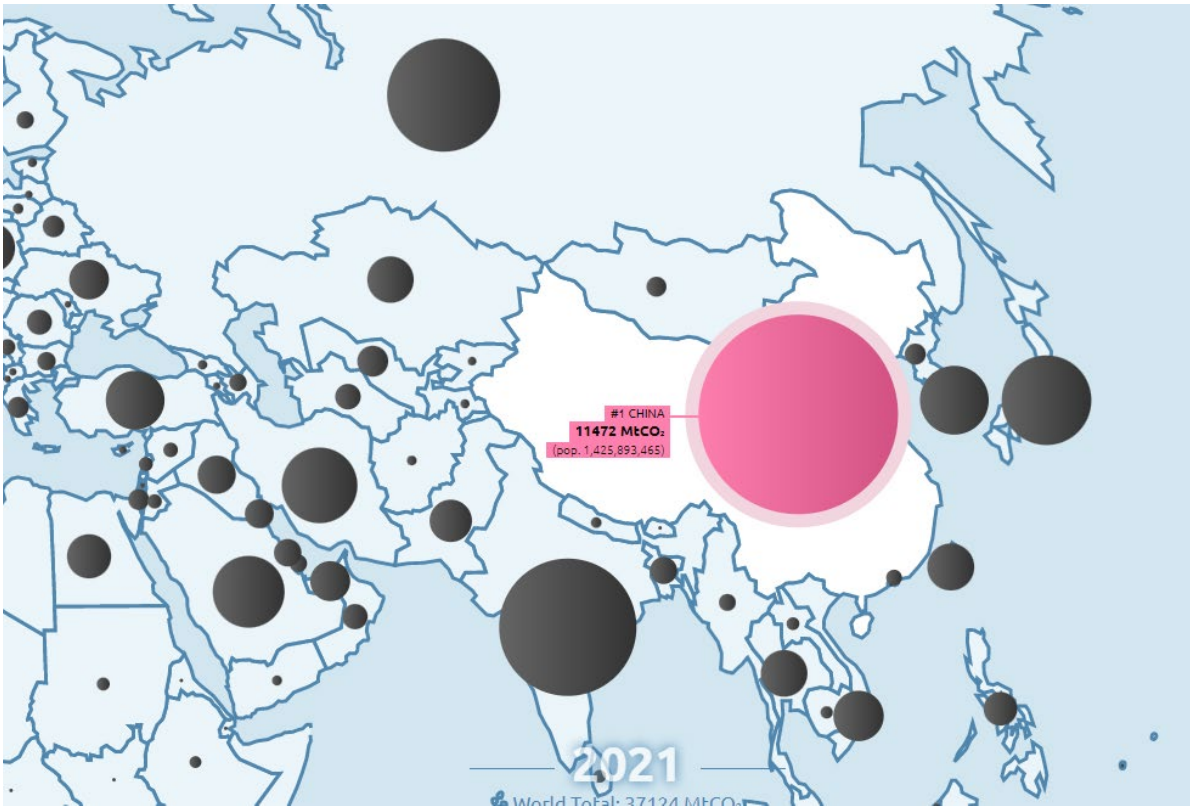


Figure 79. Zoom on China's CO_2 emissions from the Global Carbon Atlas (http://www.globalcarbonatlas.org/en/CO2-emissions)

These data constitute an interesting indicator for comparing the relative and absolute weights that countries have on global annual CO_2 emissions. However, these data are totals and include several fossil-fuel-based sources, not only the industrial emitters that we are particularly interested in for this study. Consequently, these data cannot be used for mapping the potential areas with CO_2 emitters of interest, neither at the world scale nor at the country scale (Figure 79).

However, with deeper investigation and focus on a specific concept, it should be possible to draw up an appropriate map at world scale. Coming back to the example of the CarbFix atlas (https://www.carbfix.com/atlas) presented in section 5.1.1, it enables the simultaneous display of the geological zones of interest for this CCS technology, as well as the main CO_2 emitters. When a specific CO_2 emitter is selected on the map, certain features of the facility are displayed, as illustrated in Figure 80. It can be noted that the quantity and the quality of the information provided is very much dependent on the data source: for example, very little information is available for the site in Bosnia and Herzegovina (left side of Figure 80), while for the American site, more detailed features are provided (including annual CO_2 emissions).

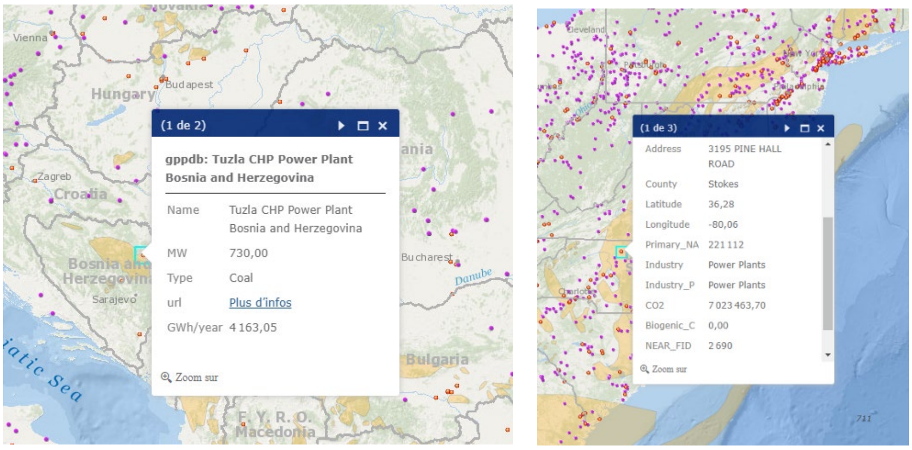


Figure 80. CarbFix atlas: zooming in and clicking on a specific CO_2 emitter provides more detailed information on some features of the industrial facility (site in Bosnia and Herzegovina on the left, site in the USA on the right).

The Climatetrace database is another example of a global database providing geolocalized information on CO_2 emitters. However, care must be taken to apply the appropriate filters to display only data related to concentrated CO_2 emissions, which are the only ones of interest for this study. Interestingly, as with the CarbFix map, it is possible to zoom in to view information at a country or even regional level. However, we found many missing industrial sites (e.g. in France) and/or some incorrect data, and we can assume that this is similar for other countries. However, this should not reduce the interest of such a map as a first-level information provider, which is particularly difficult to obtain for many regions of the world.

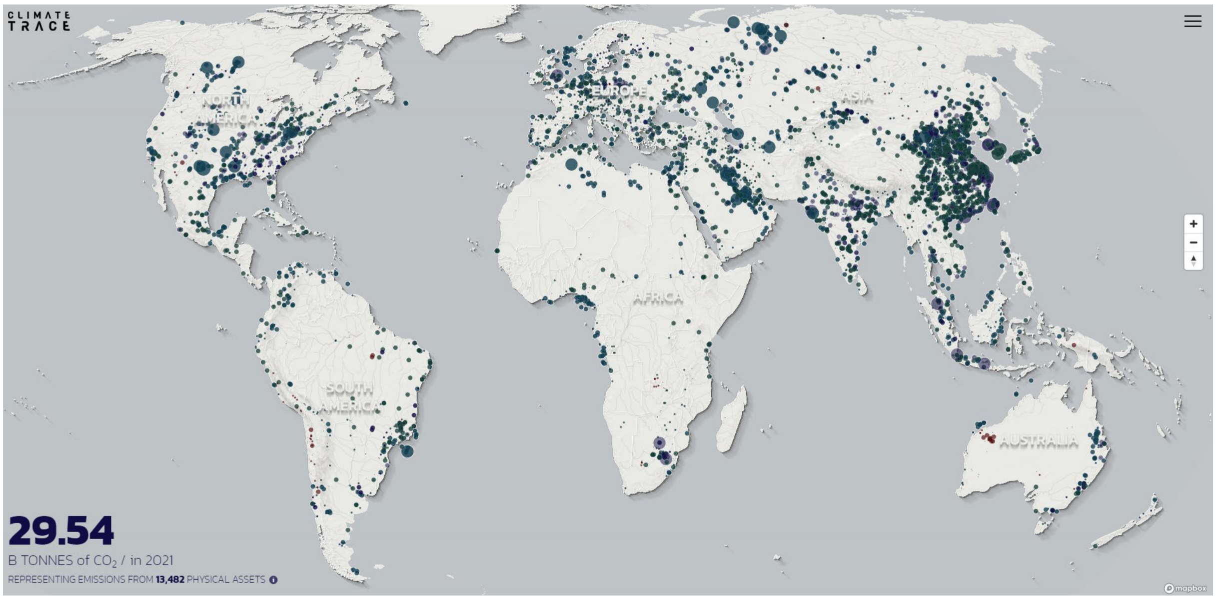


Figure 81. Climatetrace map showing geolocalized data on CO_2 emissions sites. Filters have been applied to hide diffuse emissions sources that are not relevant for this study and that are displayed by default on this map.

At such a large scale, however, both the data on industrial emitters (as shown above) and the geological information (see section 5.1.1) are insufficient to determine the feasibility of a future project in a presumably favourable geological area. These types of maps are indeed more appropriate for determining the inappropriate areas rather than the favourable ones, which in itself is valuable information.

5.2.2 *Continent scale*

An example of an exploitable dataset for Europe is that of the European Industrial Emissions Portal (EIEP) of the European Environment Agency (https://industry.eea.europa.eu/). As illustrated in Figure 82, focus is placed on industrial emissions (total per year) with an accurate geolocalization of the industrial sites in the EU Member States, Iceland, Liechtenstein, Norway, Serbia, Switzerland and the United Kingdom, from 2007 to 2020 at the date of publication of this report. Moreover, when clicking on a site, this gives access to detailed technical and administrative information, such as the exact location of a site, type of activity, CO_2 emissions history, age of the facility, permitting authority, etc. (Figure 83).

Interestingly, the raw data used for producing these maps can be downloaded from the website (https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-18), meaning that it is possible to create, with any GIS tool, a specific map containing only the data of interest on a specific region of Europe. However, looking in more detail at more recent years (2019, 2020), data from several countries are missing: emissions from the United Kingdom, Germany, Italy, Norway are no longer reported (Figure 84). In addition, when the raw data are downloaded, certain data are corrupted: about ~2-3% of the cases have wrong site coordinates (corresponding emitters not located in the relevant country).

Another drawback of this database lies in the CO_2 emission threshold that is set at a value of 100 kt CO_2/yr. This value matches with the needs of several concepts aiming at storing medium-to-large amounts of CO_2 (e.g. concepts requiring an external CO_2 source with a storage objective above 3 Mt CO_2 over 30 years in Figure 51). However, no information is provided for the other concepts targeting smaller storage objectives (those below 3 Mt of external source over 30 years in Figure 51). For this latter category of concepts, supplementary work is needed, probably at a more local scale, as exemplified in the next section.

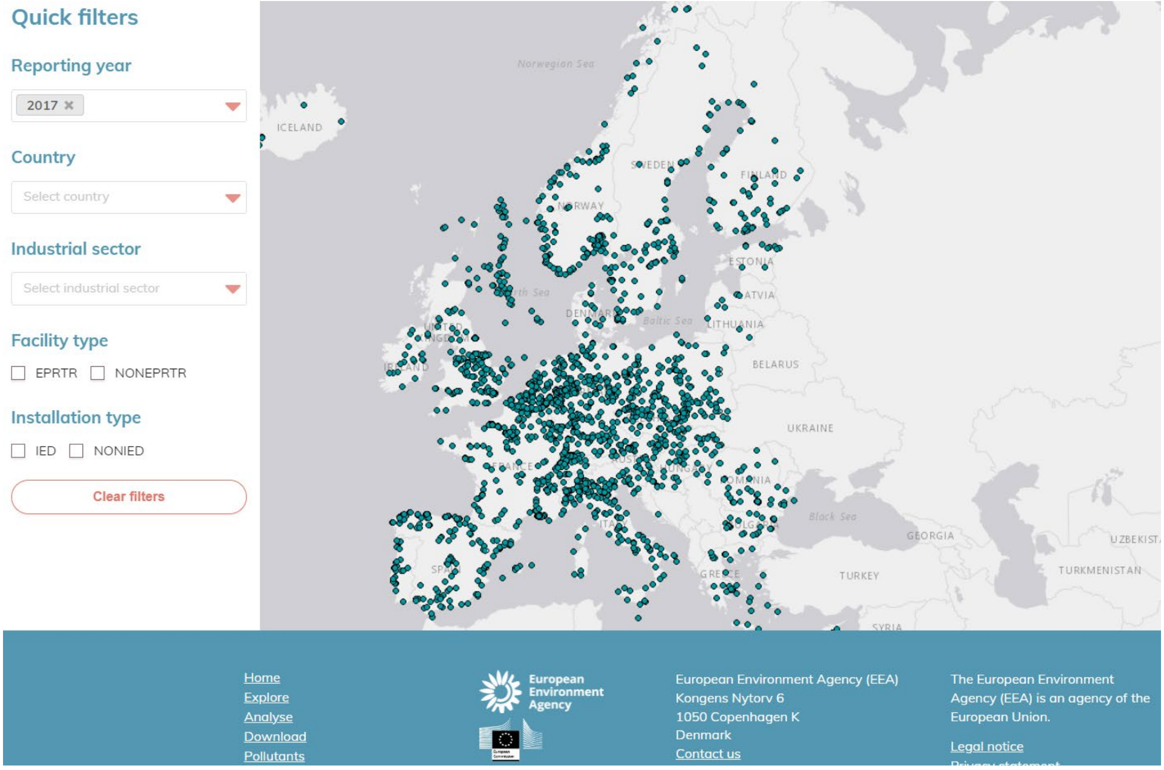


Figure 82. Map of the main industrial CO_2 emitters in Europe (year 2017) accessible from the European Industrial Emissions Portal (https://industry.eea.europa.eu/explore/explore-data-map/map)

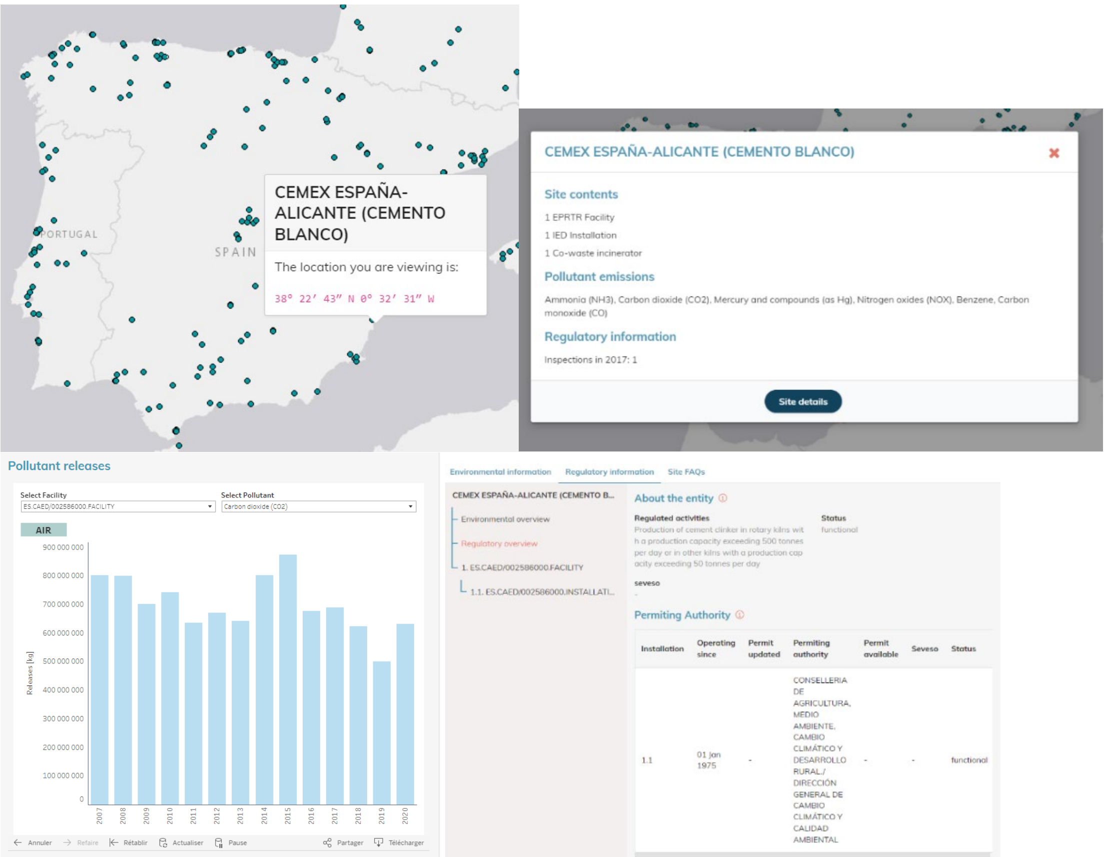


Figure 83. Data accessible by clicking on a specific site on the map of CO_2 emitters on the European Industrial Emissions Portal (https://industry.eea.europa.eu/explore/explore-data-map/map).

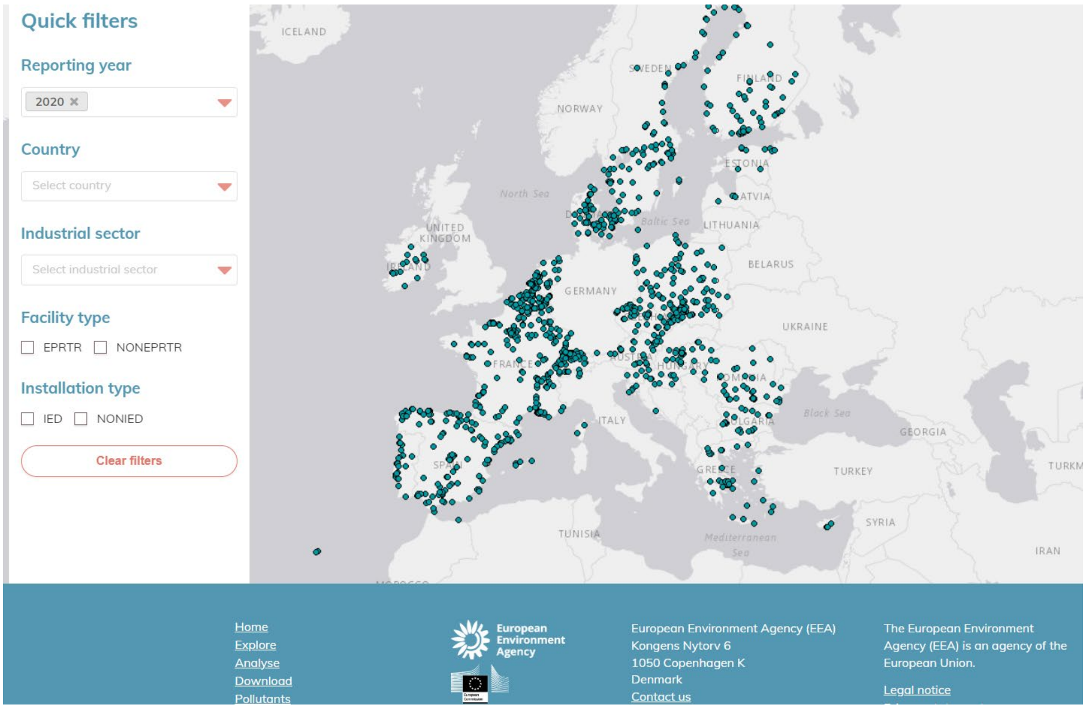


Figure 84. Map of the main industrial CO_2 emitters in Europe (year 2020) accessible from the European Industrial Emissions Portal (https://industry.eea.europa.eu/explore/explore-data-map/map)

Another example of an accessible data set at continental scale is the Australian government's Emissions Reduction Fund project's website (Figure 85). The Emissions Reduction Fund is a voluntary scheme that aims to provide incentives for a range of organizations and individuals to adopt new practices and technologies to reduce their emissions. Interestingly, this map does not provide direct information on CO_2 but showcases data on emissions reductions (through storage or avoidance). When a specific site is selected, the information provided is displayed in terms of Australian Carbon Credit Units (ACCU) issued (30,191 t CO_2e in the example of Figure 86). "Data displayed under 'ACCUs issued' throughout the map represents the total ACCUs issued to a project to date—including projects with and without a government contract. Each ACCU issued equals one tonne of carbon dioxide equivalent (tCO2-e) stored or avoided by a project."

Figure 85. Map of landfill and waste sites in Australia (Emissions Reduction Fund project's website https://www.cleanenergyregulator.gov.au/maps/Pages/erf-projects/index.html).

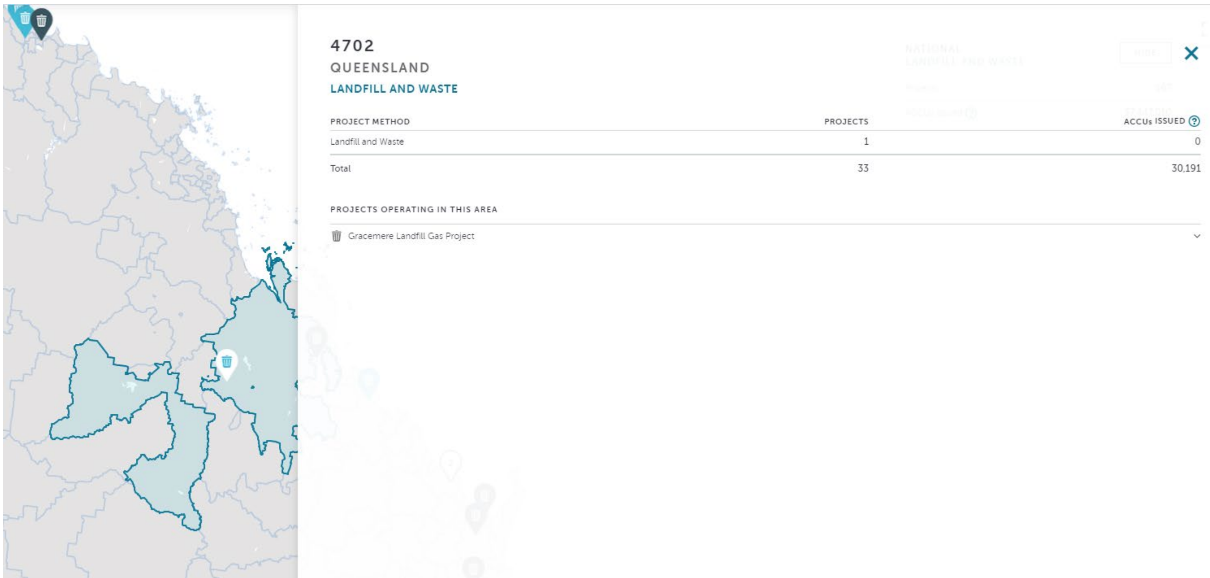


Figure 86. Data accessible by clicking on a specific site of the Australian Emissions Reduction Fund project's website.

These data cannot be directly exploited for the purpose of this study but could be used to locate areas of interest for various types of activity, with probable associated CO_2 emissions, despite no value being available.

Other data can be found on total of emissions by country on other continents, as either report or figures directly available on websites (OECD, Our World in Data, Global Carbon Atlas). The major drawback of such data, especially for the present study, is that they are global, and thus not geolocalized. This emphasises the need for such data services and the great value of a site like the EIEP or Climatetrace, even if some data are erroneous or missing.

5.2.3 *Country/state/region scale*

At the scale of a country, a state or a region, more databases exist. Three examples providing webservices from which it is possible to directly visualize general maps, to display more local information, and download raw data, are given below.

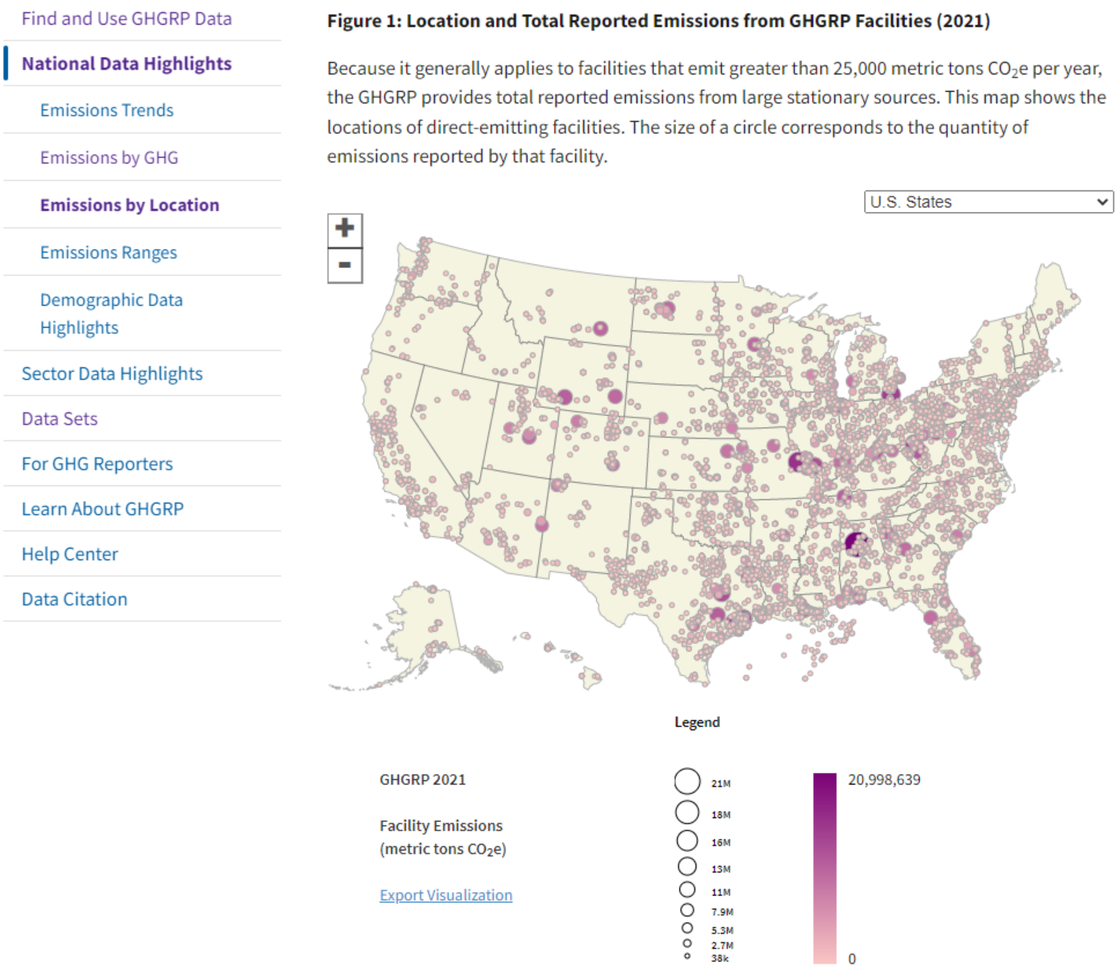


Figure 87. interactive map of the US industrial CO_2 emitters (available on the US-EPA website https://www.epa.gov/ghgreporting/ghgrp-emissions-location)

Website of the Greenhouse Gas Reporting Program (GHGRP) of the US Environmental Protection Agency (US-EPA).

Despite the United States being closer to the size of a continent, the details and exhaustiveness of the data available is remarkable (Figure 87). Contrary to the CO_2 emitters map in Europe (Figure 82), the data presented here are at first glance more detailed (diameter of the circles is proportional to the emission range) and the threshold is at 25 kt CO_2/yr, which potentially greatly increases the number of sites and concepts matching possibilities.

By clicking on any circle on this map, the user immediately has access to key information on the emitter (see Figure 88): name of the facility, industrial sector, last reported emissions (2021 when this report was written). If more detailed information, notably at the state scale (or even at the city scale), is expected, it is advised to use the Facility Level Information on GreenHouse gases Tool (FLIGHT, https://ghgdata.epa.gov/ghgp/main.do) which greatly facilitates navigation and gives access to more local and detailed information (cf. Figure 89 and Figure 90).

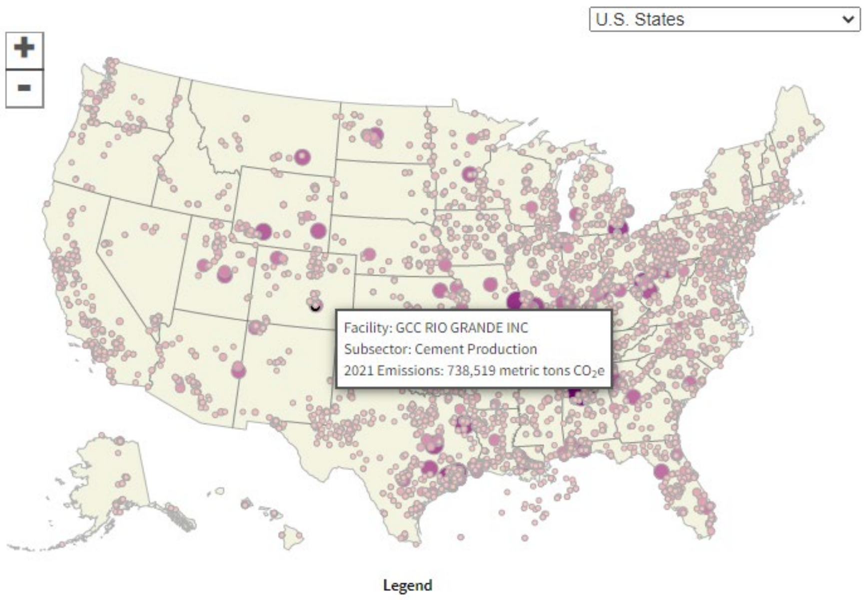


Figure 88. Summary information on the selected emitter, here a cement production plant (US-EPA GHG emissions' interactive map https://www.epa.gov/ghgreporting/ghgrp-emissions-location).

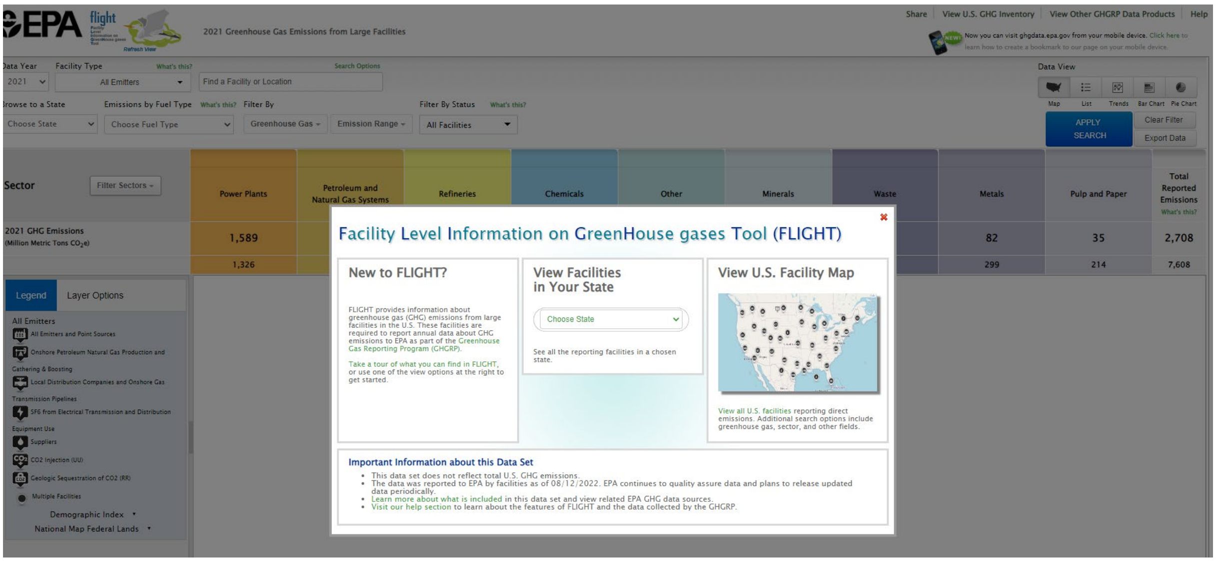


Figure 89. FLIGHT (Facility Level Information on GreenHouse gases Tool) homepage showing the selection of a state and navigation to access detailed information on a specific CO_2 emitter (US-EPA website https://ghgdata.epa.gov/ghgp/main.do).

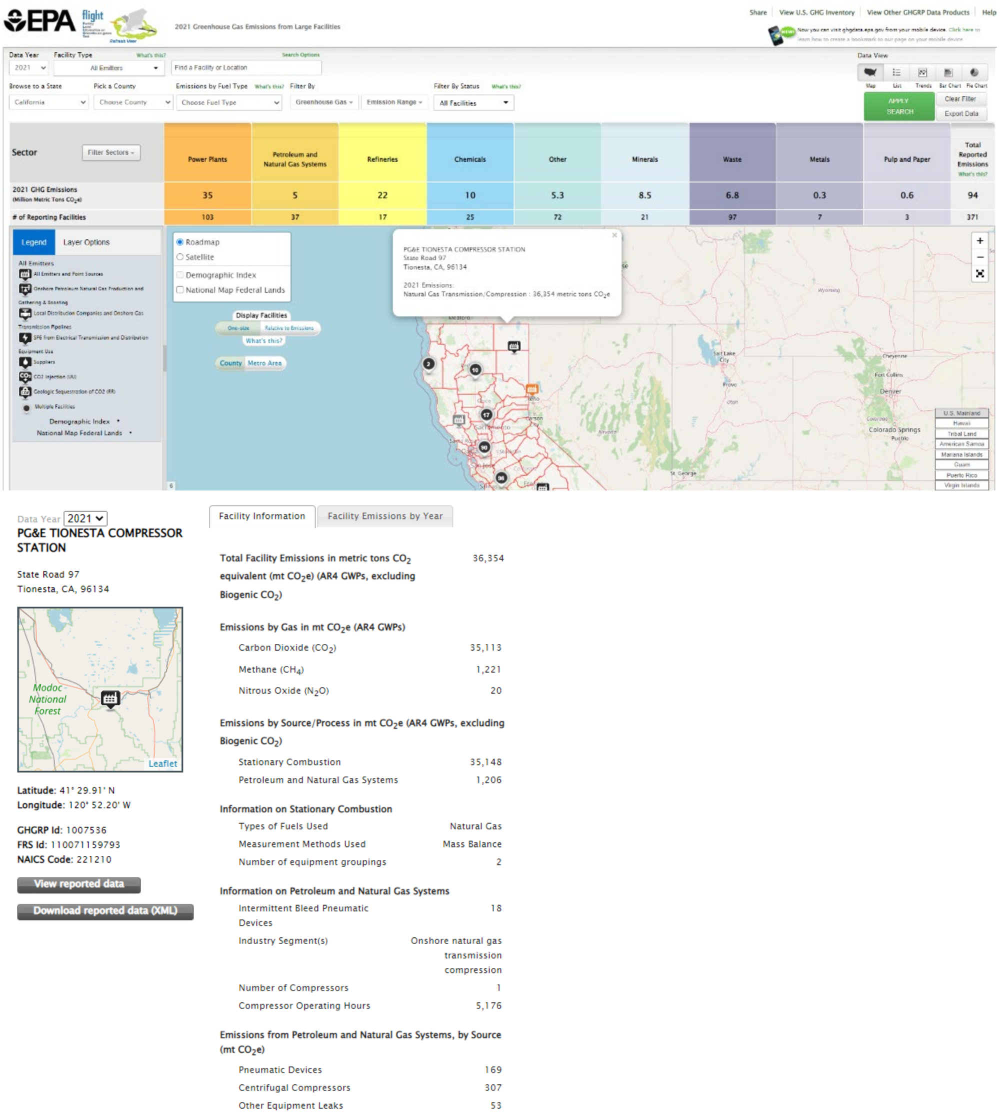


Figure 90. Detailed information for a specific emitting facility (natural gas transmission/compression plant in California) accessible through the FLIGHT interface

Web service offered by the UK's National Atmospheric Emissions Inventory (Figure 91): This interactive map shows CO_2 totals for 2019. The user can choose to show different sectors on the map (industry in Figure 91) and select a specific local authority by clicking on the corresponding area on the map, or selecting the name from the menu next to the map. Once a local authority region has been selected, any point sources within that region will be shown and further details can be viewed by clicking on the icon.

When selecting and zooming in on an area, the information displayed on the total statistics of the local authority is quite exhaustive (see table on the right in Figure 92). The location of sites is shown with black/grey circles of variable diameter (proportional to the amount of CO_2 emitted by the corresponding facility, although no scale is indicated). When clicking on one of these circles, the amount of CO_2 is explicitly indicated. Curiously, the information is not at all consistent between what is indicated here and the totals displayed in the previously mentioned table. In Figure 92, annual totals (2019) are displayed at 54.5 kt CO_2 for the Chesterfield (England) local authority, while according to Figure 93, one site (the largest circle) emits only 71 t CO_2 (such a low value does not make sense) and another has a null emission rate. After verification, the two other circles also have a null emission rate. This issue was observed for several regions of this map. Data discrepancies exist between totals and site information.

Considering orders of magnitude, the totals are considered more reliable than (corrupted) site information. This type of map remains extremely useful in the perspective of building a dedicated GIS map for ranking the most favourable areas matching the requested criteria for one of the concepts to be deployed in the future. Ideally, geolocalized raw data should be downloadable. However, looking at the "download" menu of the website (https://www.gov.uk/government/collections/uk-local-authority-and-regional-greenhouse-gas-emissions-national-statistics#carbon-dioxide-emissions), it would appear that only totals without details and raw data of the sites are available.

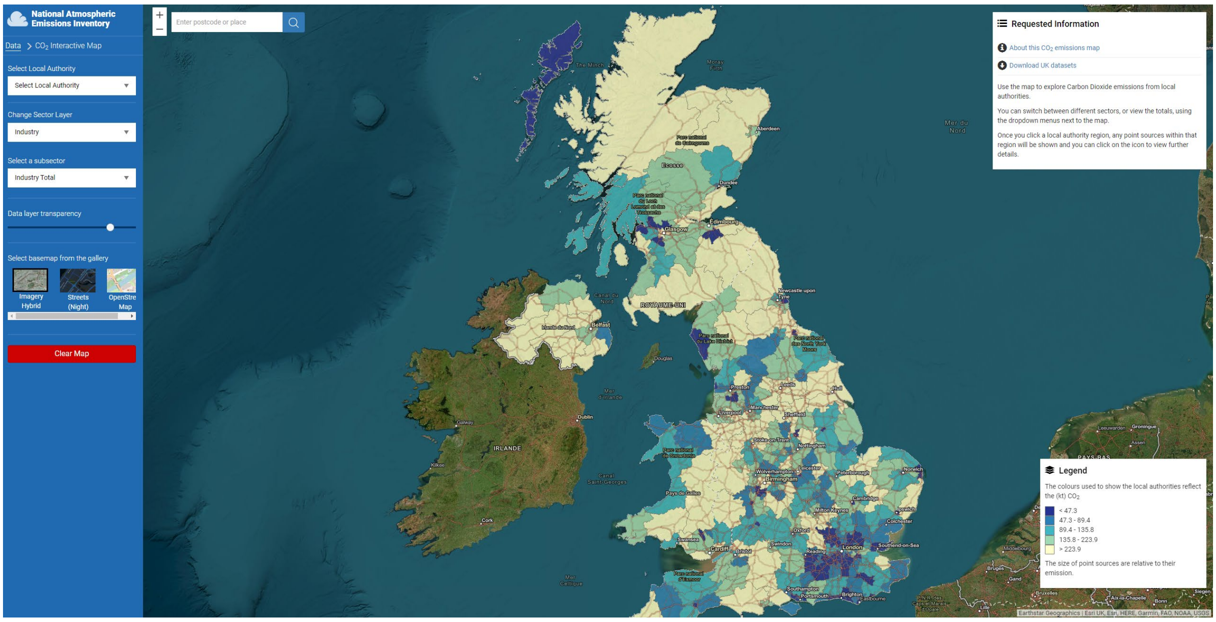


Figure 91. Interactive map of the CO_2 emissions for the industry sector in the UK, 2019 (UK's National Atmospheric Emissions Inventory website https://naei.beis.gov.uk/laco2app/).

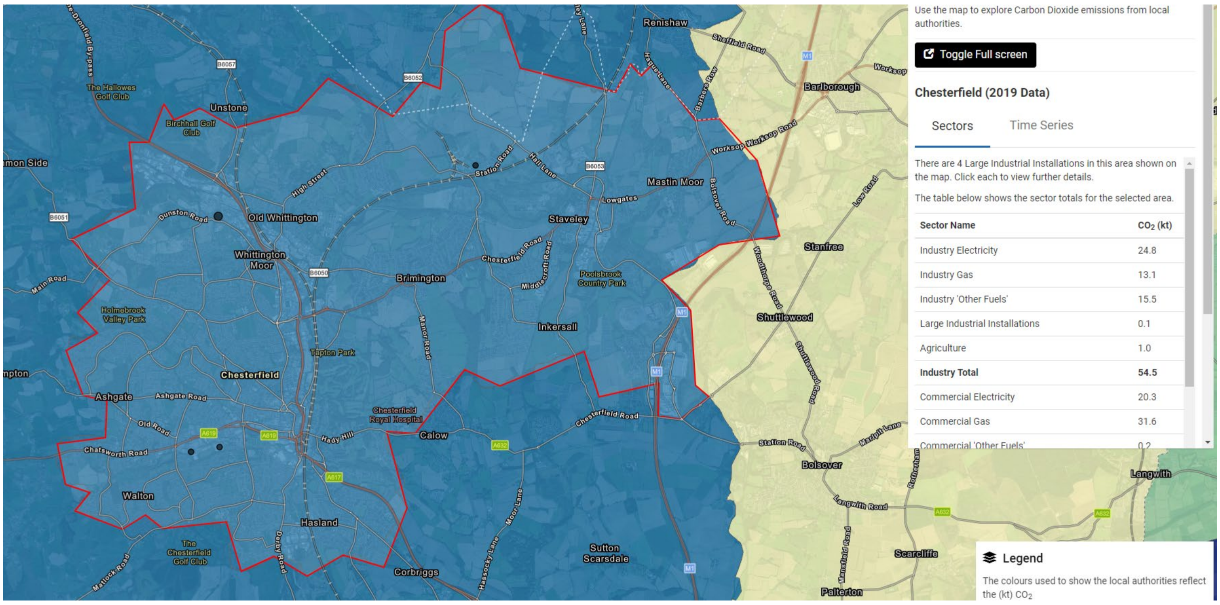


Figure 92. Zoom of the selected area of Chesterfield (England) and corresponding statistics (on the right) showing annual total emissions of 54.5 kt CO_2 (2019) (UK's National Atmospheric Emissions Inventory website https://naei.beis.gov.uk/laco2app/).

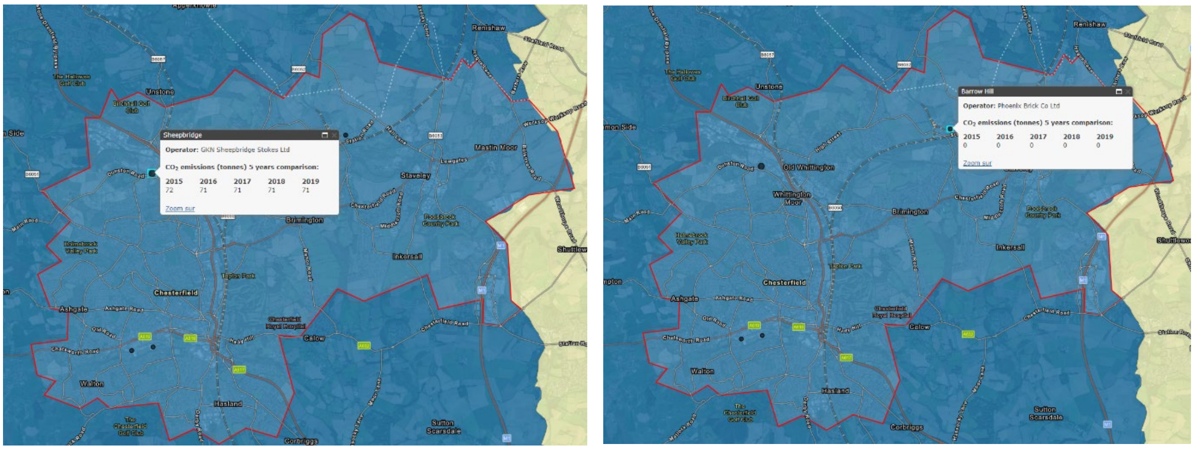


Figure 93. Detailed information on annual CO_2 emissions (in tonnes) for two of the four large industrial installations of the selected area (Chesterfield, England). (UK's National Atmospheric Emissions Inventory website https://naei.beis.gov.uk/laco2app/).

Dataset provided by the French Registre des Emissions Polluantes on the Ministry of Ecological Transition and Territorial Cohesion's Georisques website (https://www.georisques.gouv.fr/risques/registre-des-emissions-polluantes):

The information provided here is quite exhaustive for all types of air, soil, and water pollutants. CO_2 is of course among the data available, based on annual declared amounts by industrial facilities emitting more than 10 kt CO_2/yr (declaration to the administration is mandatory for all these sites).

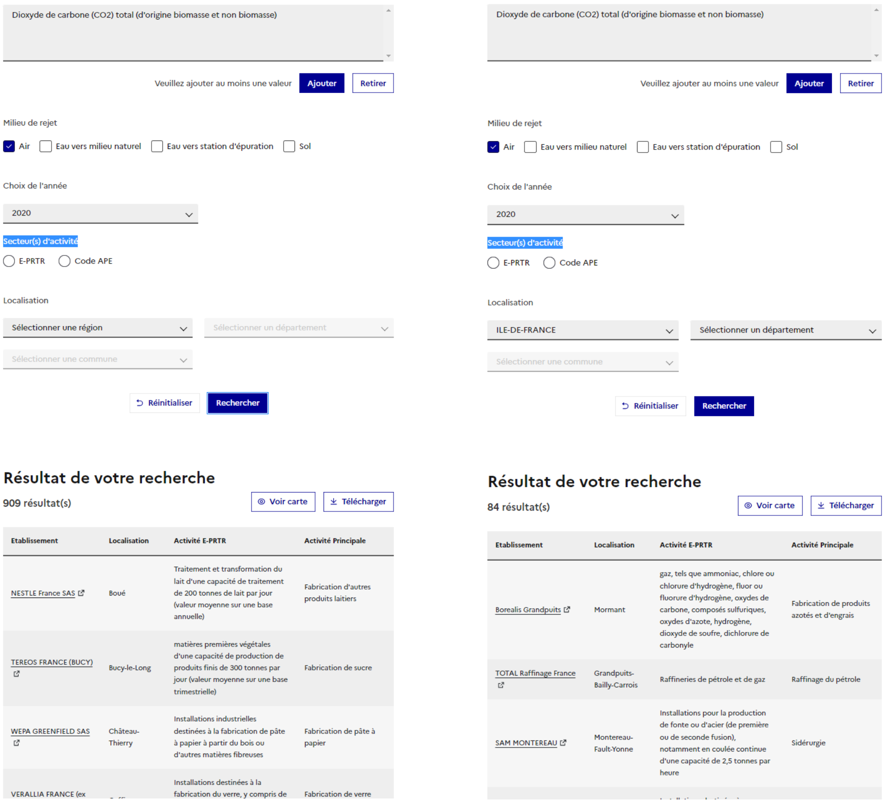
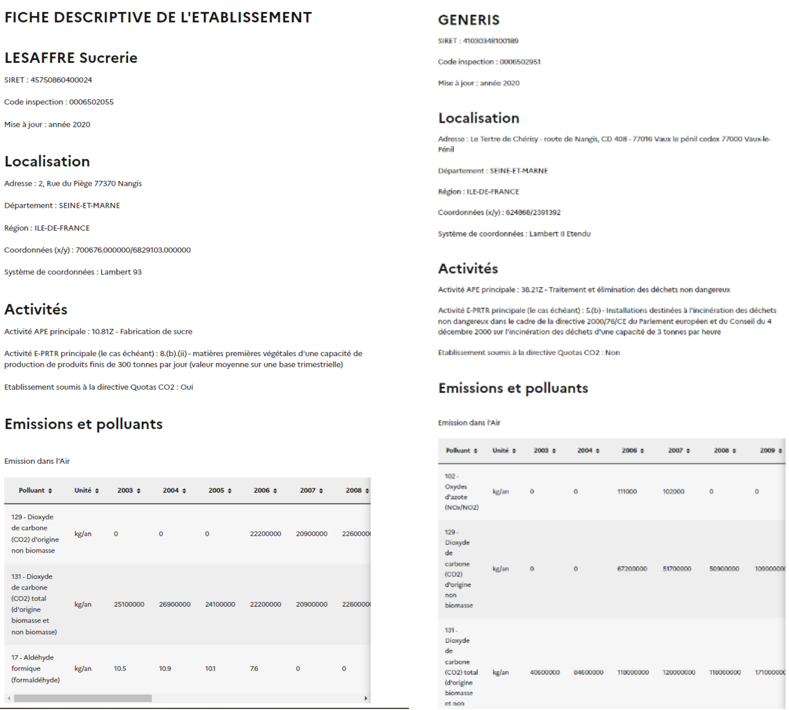


Figure 94. Datasets on CO_2 emitters available on the French Registre des Emissions Polluantes on the Ministry of Ecological Transition and Territorial Cohesion's Georisques website. At national scale on the left (909 sites in 2020) and at Region Ile-de-France scale (Paris area) on the right (84 sites in 2020).

This website is currently evolving and some functions do not work properly (data downloads are partial, filters do not work on the interactive map making it practically unusable). Another drawback is that the data are in French, which is not user-friendly for non-French-speaking teams. Interestingly, data can be displayed at the national, regional, departmental, and town scale, making the information provided very useful for the present study, as we can eventually access details for the country at the site scale (see Figure 94 and Figure 95). It is worth noting that CO_2 emissions are expressed in kg CO_2/yr, which is not very convenient, as it obliges the user to handle many zeros (especially for large emitters in the 1 Mt/yr range), although it is easy to convert into kt CO_2/yr once the datasets are downloaded and imported in any spreadsheet programme. As with the European Industrial Emissions Portal, a few corrupted/missing data were observed, but, in general, the information provided is reliable.


FICHE DESCRIPTIVE DE L'ETABLISSEMENT

LESAFFRE Sucrerie

SIRET : 45750860400024

Code inspection : 0006502055

Mise à jour : année 2020

Localisation

Adresse : 2, Rue du Piège 77370 Nangis

Département : SEINE-ET-MARNE

Région : ILE-DE-FRANCE

Coordonnées (x/y) : 700676.000000/6829103.000000

Système de coordonnées : Lambert 93

Activités

Activité APE principale : 10.81Z - Fabrication de sucre

Activité E-PRTR principale (le cas échéant) : 8.(b).(ii) - matières premières végétales d'une capacité de production de produits finis de 300 tonnes par jour (valeur moyenne sur une base trimestrielle)

Etablissement soumis à la directive Quotas CO2 : Oui

Emissions et polluants

Emission dans l'Air

Polluant	Unité	2003	2004	2005	2006	2007	2008
129 - Dioxyde de carbone (CO2) d'origine non biomasse	kg/an	0	0	0	22200000	20900000	2260000
131 - Dioxyde de carbone (CO2) total (d'origine biomasse et non biomasse)	kg/an	25100000	26900000	24100000	22200000	20900000	2260000
17 - Aldéhyde formique (formaldéhyde)	kg/an	10.5	10.9	10.1	7.6	0	0

GENERIS

SIRET : 41030348100189

Code inspection : 0006502951

Mise à jour : année 2020

Localisation

Adresse : Le Tertre de Chérisy - route de Nangis, CD 408 - 77016 Vaux le pénil cedex 77000 Vaux-le-Pénil

Département : SEINE-ET-MARNE

Région : ILE-DE-FRANCE

Coordonnées (x/y) : 624868/2391392

Système de coordonnées : Lambert II Etendu

Activités

Activité APE principale : 38.21Z - Traitement et élimination des déchets non dangereux

Activité E-PRTR principale (le cas échéant) : 5.(b) - Installations destinées à l'incinération des déchets non dangereux dans le cadre de la directive 2000/76/CE du Parlement européen et du Conseil du 4 décembre 2000 sur l'incinération des déchets d'une capacité de 3 tonnes par heure

Etablissement soumis à la directive Quotas CO2 : Non

Emissions et polluants

Emission dans l'Air

Polluant	Unité	2003	2004	2006	2007	2008	2009
102 - Oxydes d'azote (NOx/NO2)	kg/an	0	0	111000	102000	0	0
129 - Dioxyde de carbone (CO2) d'origine non biomasse	kg/an	0	0	67200000	51700000	50900000	10900000
131 - Dioxyde de carbone (CO2) total (d'origine biomasse et non	kg/an	40600000	84600000	118000000	120000000	118000000	1710000

Figure 95. Detailed information for two sites of the Ile-de-France region (Paris area) extracted from the French Registre des Emissions Polluantes on the Ministry of Ecological Transition and Territorial Cohesion's Georisques website. A sugar factory on the left and a waste incineration plant on the right. Emission rates are in kg/yr.

5.3 Combining data to assess favourable areas for combined geothermal energy production and CCS: some examples

The data on CCS potential and geothermal resources presented in the previous subsections are the core of the assessment strategy on favourable areas for combined geothermal energy production and CCS. It is a matter of compromise to find the best balance between the availability of raw data, the achievable accuracy (generally highly dependent on the spatial scale considered), the accessibility to non-public data (possibly having to negotiate with owners and potential end-users of a specific concept), and the feasibility (technical and financial) of acquiring supplementary data.

In order to illustrate the sort of maps that can be produced from publicly available data, we have created two maps at different scales: France and Europe. The aim of these maps is to show the potential favourable areas for combined use of geothermal energy and CCS, either with supercritical or dissolved CO_2. To widen the applicability of these maps to include concepts using an external source of CO_2, we included data on industrial CO_2 emitters.

An important first step is to combine on the same maps both the locations of CO_2 sources (industrial emitters in general) and the suitable areas for geothermal energy production. This is crucial to determine the pre-feasibility of implementing a specific concept by checking the adequacy between the primary objectives (e.g. maximizing CCS and/or geothermal energy production) and the intrinsic capacities of the reservoir in terms of injectivity, fluid temperature, porosity and storage capacity. For example, Iceland and New Zealand have high-enthalpy geothermal areas and reservoirs capable of storing large amounts of CO_2. However, these areas lack large industrial emitters that could provide the CO_2 source needed to feed processes such as CarbFix, CPG or EGS. In these cases, importing CO_2 from abroad, as is being considered in Iceland, for example, probably isn't the best environmental strategy in terms of global CO_2 avoidance or mitigation. Conversely, in locations where large CO_2 emitters are present, and assuming favourable local reservoir properties for low-enthalpy geothermal energy production (as may be the case in the Paris Basin, for example), concepts with limited CO_2 storage capacities (e.g. CO_2-DISSOLVED) are not the best options to consider for significant CO_2 emissions abatement. More generally, and for all these hybrid concepts, the match between needs and resources is really the key to potential viability. The maps presented below are intended to provide an initial screening tool before further studies are carried out at a more local scale.

5.3.1 *Map of potential favourable areas for combined use of geothermal energy and CCS in France*

Firstly, data from the AtlasGTH resource map (Maurel and Bonnefon, 2022; Caritg et al., 2018), which is an improved version of the CO_2STOP CCS potential map, were combined with data on industrial emitters from the French “Registre des Emissions Polluantes” database. These data were then included in a GIS, which forms the basis of the map in Figure 96.

In France, the most favourable locations for deep geothermal energy exploitation in hydrothermal systems and for CO_2 storage are in sedimentary basins (Figure 96). Situated within these sedimentary basins, Paris, Marseille and their surrounding areas, which have many concentrated industrial emitters, have access to nearby suitable CO_2 storage capacity. Conversely, Lyon and its surroundings, despite having many emitters and a geothermal resource that can be exploited, does not have high identified CO_2 - Figure 96).

In the results of the CO_2STOP project, the rifts zones of the Upper Rhine Graben, Bresse, and Limagne are not considered as potentially favourable areas for storage because of the presence of large faults, which could represent potential escape pathways. However, for storage at a smaller scale, or for CO_2 storage in a dissolved form, these regions may be of interest, as confirmed by the conclusions of the GeORG project.

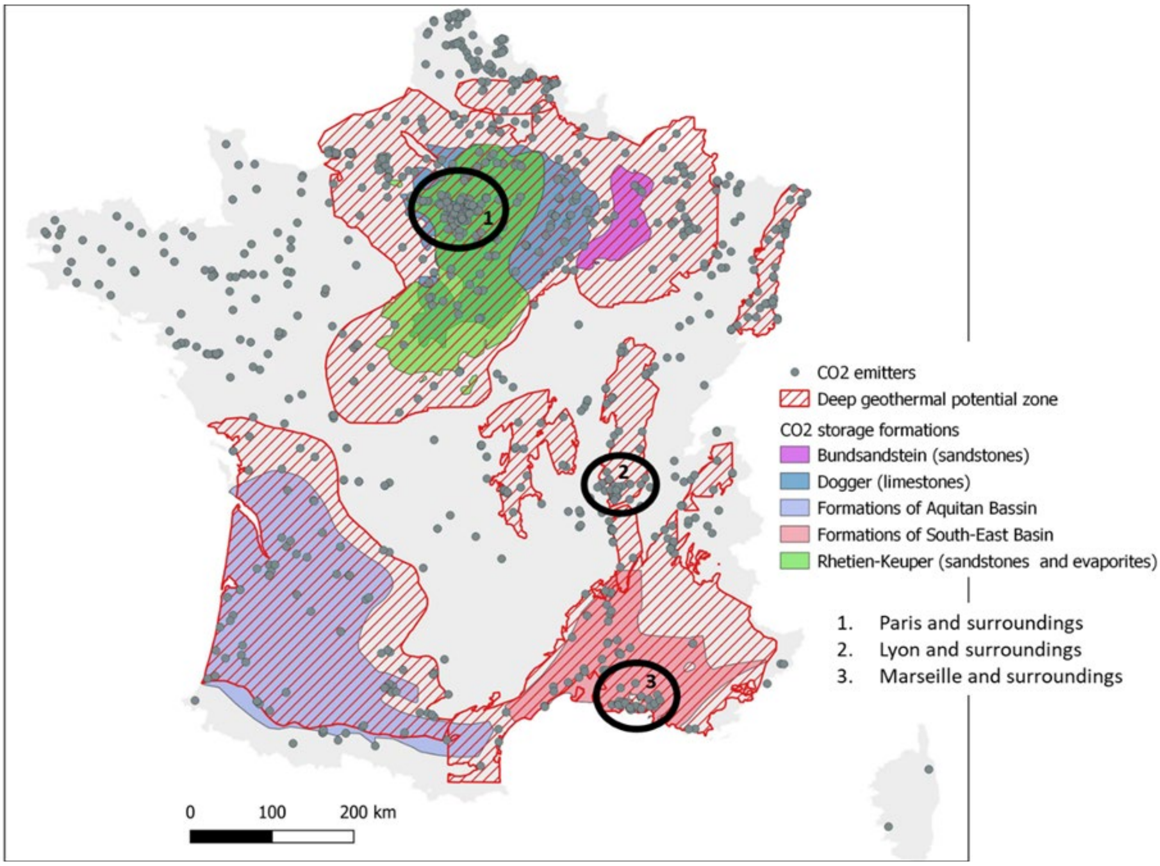


Figure 96. Map of France showing an initial assessment of favourable areas for geothermal heat production and CO_2 storage, created from combined data of the GeORG, CO_2STOP, and AtlasGTH projects. Main industrial CO_2 emitters are represented by grey circles.

5.3.2 *Map of potential favourable areas for combined use of geothermal energy and CCS in Europe*

At a European scale (Figure 97), the geothermal resources map for district heating development indicates favourable areas in sedimentary basins with temperatures above or equal to 50°C at 1000 m depth. This depth constitutes a somewhat arbitrary limit for geothermal exploitation, which does not preclude any geothermal exploitation if the 50°C isotherm was deeper.

From this map, and consistent with a national evaluation of France (Figure 96), the Paris basin appears to be a good candidate for geothermal energy production and for CO_2 storage, as well as the Pannonian Basin (Hungary and neighbouring countries), the eastern part of the North German Basin, the Molasse Basin north of the European Alps, and the Campine Basin in Belgium and The Netherlands.

This map could be further refined to take into account other types of geothermal resources and small emitters that are of interest for some concepts (e.g. CO_2-DISSOLVED). Note that the map only shows industrial sites emitting more than 100 kt CO_2/yr as given by the European Industrial Emissions Portal.

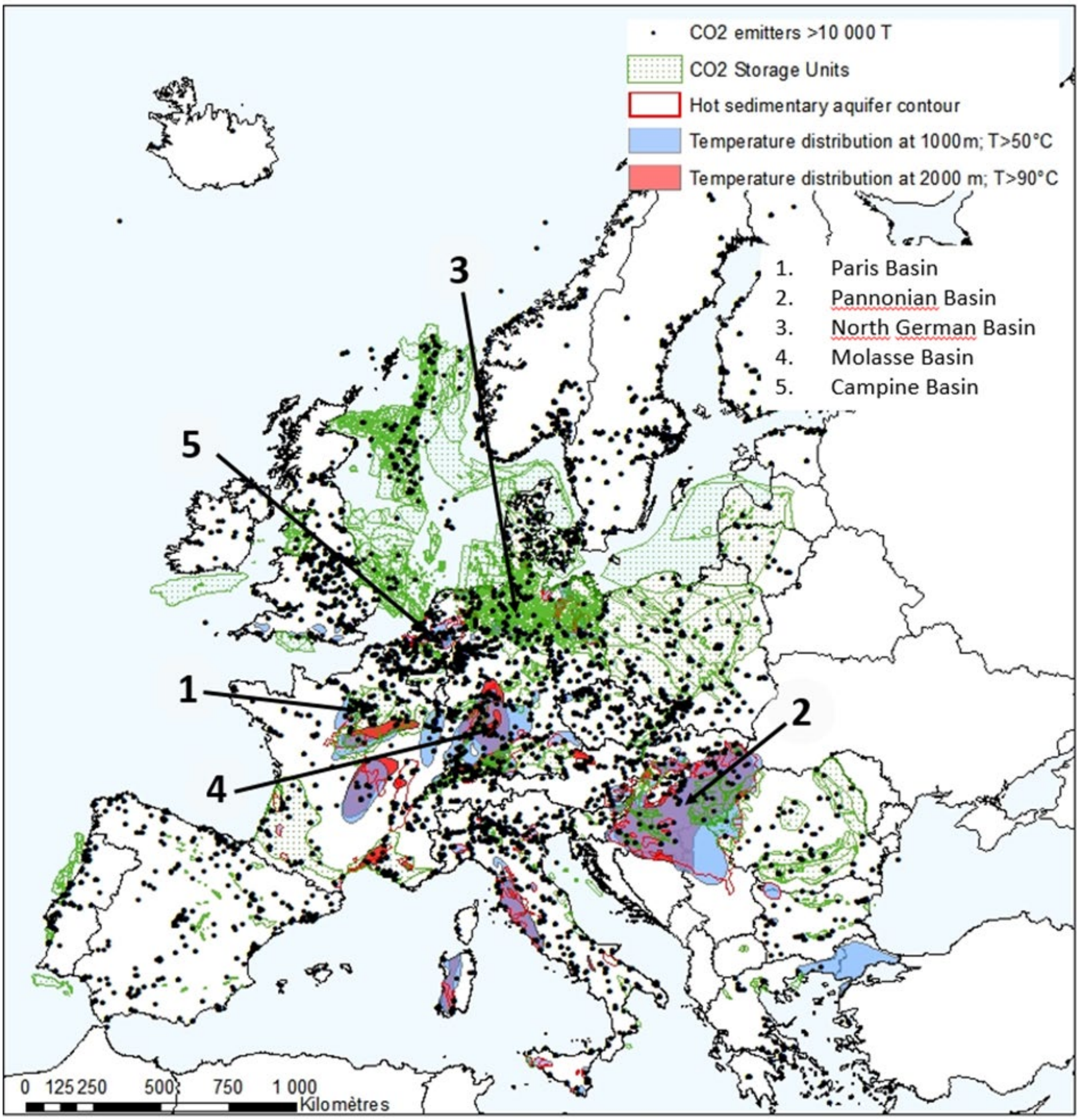


Figure 97. Map of Europe showing the potential for geothermal resources and CO_2 storage, created using geothermal data from the project GeoDH. Industrial emitters > 100 kt CO_2/yr are represented by black circles (European Industrial Emissions Portal).

6 Conclusion and perspectives

The extensive literature review carried out in the first part of this study aimed to provide an overview of all concepts involving the hybrid use of underground resources for CO_2 capture and storage (CCS) and geothermal energy production. More than 15 concepts were identified, and a classification was necessary to avoid confusion as many of them had relatively similar characteristics at first sight. This classification work led to the definition of four main categories of concepts, lying between pure CCS on the one hand and pure geothermal on the other:

1) Use of supercritical CO_2 as a heat vector for geothermal energy production
2) Water-driven geothermal concepts with CO_2 (re)injection either from the geothermal fluid itself or from an external source.
3) Other synergetic uses with lighter hybridization
4) Borderline concepts with respect to the scope of the study.

For each concept and to provide a more synthetic view, a set of infographics were developed providing the big picture and the key features.

Another aim of this study was to compare these concepts in terms of expected performance. This was probably the most complex part of the work, given the relatively large heterogeneity between the levels of description, knowledge, feedback (where pilots exist) and overall maturity of all the concepts.

We defined Key Performance Indicators (KPIs) to allow quantitative comparison between concepts: 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). We did not use the TRL scale as it was not adapted to the characteristics of this study, dealing with untested concepts (thus low TRL by definition), a novel combination of commercial technology, and heterogeneity in the perimeter of the concepts. For each of these KPIs we propose a score (between 1 and 5; the higher, the better). However, given the wide variability of the criteria typology and the inevitable subjectivity of this approach, we suggest that the reader add their own scores and makes their own weighted average to obtain an overall score for all concepts of interest. To facilitate this, all these scores and associated comments have been included in an attached spreadsheet file that each reader can easily modify according to his/her own vision/knowledge of each concept.

Table 12 provides an overview of the scores assigned by the authors of this report, which, as mentioned above, can be debatable. From this ranking, it appears that 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. Note that, according to our evaluation, CO_2-EGS and CPG-ES have the lowest scores for ensuring CO_2 storage, which requires the inclusion of high-level monitoring procedures when setting up a first pilot to measure actual performance. In addition, the inclusion of large amounts of CO_2 requires that the CO_2 is effectively available, either from a nearby large industrial facility with high CO_2 emissions, or from an existing (or to be built) infrastructure that can deliver CO_2 on site. Although the former is by far the preferred option (the global CO_2 balance is much more favourable if CO_2 is not transported from a distant location), having a high-capacity storage site close to a large CO_2-emitting facility or hub places additional constraints on the feasibility of such a project.

Conversely, 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, CO_2 re-injection). Generally speaking, the lower the CO_2 content, the easier it will be to manage the permitting process and the operation of the plant itself, and probably also to gain social acceptance. These concepts, taken individually, will however have a much smaller impact on reducing CO_2 emissions on a global scale than the concepts involving CO_2 as a heat vector. Consequently, they require a relatively high level of replicability to have a measurable environmental impact on a regional or national scale.

The replicability potential, i.e. the attempt to answer the question "where can this concept work?" is then the key to a global performance comparison between concepts. The question is simple, but the answer is much more complex, as it depends on the availability of information on the subsurface geology, hydrogeology, geochemistry, as well as on the industrial landscape of a given region in terms of CO_2 emissions and, in some cases, the energy needs of the emitter itself (in case geothermal energy could provide part of this energy) or of the proximal infrastructures. Great heterogeneity is observed in the quantity and quality of the data available, depending on the region of the world considered. The choice has been made to present examples of some interesting datasets available in the literature or, more often, through websites or web services. This review was carried out from the world level down to the country/region level. Unsurprisingly, narrowing the scope to a small region generally gives access to more detailed data, but it is equally important to have a large-scale overview in order to first identify regions where it would be interesting to focus on. These datasets form the core of future cartographic work, which is essential to identify the main regions of interest for the implementation of a specific concept. Ultimately, however, an in-depth local study will be required before a final conclusion can be drawn on the feasibility of implementing a concept in a particular area. In this report, we present two examples of maps produced as part of this study, which should be considered as a methodological guide for future detailed mapping work.

The results of this study show that much work is currently being done to design and develop solutions based on the hybrid use of the subsurface to produce geothermal heat or electricity that could be largely decarbonized and/or combined with CCS of an external industrial CO_2 source. Of all the concepts described in this report, the most advanced are at the demonstration stage or in the process of preparing a first pilot. For the others, a pilot is essential to validate the concept and measure its real performance, but many of the concepts presented first need to increase their TRL. The difficulty in increasing the TRL to 5 or 6 (technology validation or demonstration in a relevant environment) for systems that rely on the use of wells (both for geothermal energy recovery and for CO_2 injection) is mainly related to the budgetary requirements for either accessing existing wells or drilling dedicated wells. The TRL gap between one or more concepts described in technical papers (TRL 1-2) and first tests in wells is huge. In addition, the core of the technology is likely to make laboratory testing unsuitable to reach only intermediate TRL (TRL 3-4).

As mentioned above, this raises the question of the appropriateness of TRL to characterize the level of development of such hybrid concepts, where technological parts with high TRL when considered separately are assembled (e.g. a geothermal doublet and a CO_2 injection well). However, adaptation to given TRLs between the beginning and the end of a project is very often one of the eligibility criteria of many calls for proposals. This is typically not favourable for hybrid projects such as those considered here. Moreover, as this type of concept by definition combines two topics (geothermal on the one hand, CCS on the other), it is also difficult to meet the requirements of calls that consider only one of these topics, and we now need to see calls specifically dedicated to hybrid concepts. It therefore appears that such calls should first adapt both their eligibility criteria and their topic categories, and probably also the level of funding, to make them compatible with projects requiring relatively large budgets.

Beyond purely technical considerations, the funding of such innovative concepts should be prioritized according to a key criterion: the potential for replicability. Indeed, funding a new "brilliant" concept that would have to meet so many conditions simultaneously that it could only be applied in one place in the world makes little sense in the context of an ecological transition strategy. We believe that priority for funding should be given to projects that demonstrate significant deployment potential. To this end, we would suggest developing more accessible funding for such deployment potential studies. As these studies are mostly desktop, they would require relatively small budgets to be carried out. Perhaps we could imagine two-stage calls, where the first stage would be a Deployment Potential Study with positive results being mandatory to be allowed to submit the second stage of the project (e.g. Pilot).

The development of these technologies can only be achieved through a strong involvement of stakeholders: in addition to research institutes, which are generally at the origin of these concepts, industrial companies, which are either CO_2 emitters themselves and/or ready to take on the operational development of these new technologies, should be involved as early as possible. As mentioned in the previous paragraph, without prospects for deployment, significant private financial investment cannot be expected. Among the criteria to be considered when assessing the development potential, local regulations in some countries or regions could be an obstacle to the deployment of such new concepts, even if technically validated. Therefore, in parallel with the technical and scientific work, further legislative and policy action is needed to adapt local regulations when and where necessary to avoid administrative barriers in the development and later deployment phases.

In Europe for example, the Commission has just proposed (16 March 2023) the Net-Zero Industry Act[18] to scale up manufacturing of clean technologies in the EU. Among the key actions, the Net-Zero Industry Act proposes to reduce the administrative burden to set up projects and to simplify permit-granting processes, which will improve conditions for investment in net-zero technologies, among which geothermal energy and CCUS are explicitly mentioned. In addition, and to encourage innovation, the legislation will allow Member States to set up regulatory sandboxes to test innovative net-zero technologies under flexible regulatory conditions. If adopted by the European Parliament, this new regulation is a step in the right direction and should facilitate the establishment of new pilot projects in Europe.

In Quebec, a new law was voted on in 2022[19], with the main objective of ending hydrocarbon exploration and production and the public funding of these activities. France has already promulgated a similar law in 2017[20] (the end of existing oil and gas fields exploitation is scheduled for 2040). Interestingly, the Quebec law proposes to go further and to use existing oil and gas wells for pilot projects aimed at obtaining new data to assess the CO_2 storage potential or the deep geothermal potential of a reservoir (among other activities related to the energy transition). This type of regulation will certainly facilitate the development of new CCS and deep geothermal pilot projects in the area, and could serve as a model for other regions of the world.

[18] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1665
[19] https://www.publicationsduquebec.gouv.qc.ca/fileadmin/Fichiers_client/lois_et_reglements/LoisAnnuelles/fr/2022/2022C10F.PDF
[20] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000036339396

Another important aspect to consider in order to better assess the feasibility of a concept is how much this concept is or would be beneficial in terms of CO_2 balance. However, we have clearly identified a lack of Life Cycle Analysis (LCA) for the whole chain (capture, transport if necessary, injection, storage, geothermal energy production/exploitation) in most (not to say all) of the papers examined in this study. LCA is the most appropriate tool to calculate a real and global CO_2 balance. As a first guess, we can expect that the inclusion of the CO_2 emissions generated by the construction of the infrastructure itself will clearly disadvantage concepts involving a large number of wells. Again, the smallest facilities appear to have a more favourable environmental impact. It would be interesting to compare the LCA performance of a hybrid concept with that of pure geothermal use, for which the CO_2 balance is expected to be very positive if the geothermal fluid is naturally depleted in CO_2 and the geothermal plant is built to replace a previous fossil fuel energy production plant (CO_2 emission avoidance). If we were to rank the concepts in terms of CO_2 LCA performance, we would certainly rank at the top of the list a site where a geothermal power plant replacing a previous fossil fuel power plant is used also for capturing and storing the CO_2 emissions of a local biomass plant. This would result in negative emissions with additional CO_2 avoidance due to the use of geothermal energy. Conversely, we believe that concepts such as those that rely on geothermal energy production to offset the energy penalty of capture would be at the lower end of this classification. Although probably better than pure CCS projects, where capture energy often comes from carbonated sources, we lose in this case the opportunity to use geothermal energy in the most beneficial way, not to mention the high cost of implementing such a technology.

Economic performance is of course a key condition to consider in the feasibility assessment process. However, based on the literature review, it was difficult to use this aspect as a specific KPI, as most of the systems were described in conceptual papers focusing on the technical aspects with little or no economic insight. Nevertheless, in Table 12 we have provided semi-quantitative economic information, mainly based on the complexity and size of the infrastructure, as can be expected from the technical description of the concept. Again, initial pilot data are essential to measure performance in terms of capital and operating expenditure (CAPEX and OPEX). It is likely that future work on economic evaluation will accompany the preparation phase of a first pilot, when equipment needs to be purchased and operations planned. Since pilots are never optimal in terms of economic performance, only the first commercial demonstrator will provide the opportunity to obtain sound economic data that could be further used to predict the economic performance of another commercial plant. In some cases, however, we believe that the economics of pre-feasibility studies could be greatly improved if subsurface data acquisition campaigns, which are generally expensive and can hinder the development of a new pilot at a very early stage, could benefit from incentivised public co-funding. In return, the results should be made immediately available to the scientific community so that future projects can make use of these data.

As an important economic driver, it should be noted that CO_2 avoidance and/or offsetting is already financially supported by the existence of carbon pricing mechanisms. Among these mechanisms, the Emission Trading Scheme (ETS) is probably the best known and most widely deployed. The European ETS is the world's first major carbon market (launched in 2005) and remains one of the largest[21]. More recently (2021), China's national ETS came into operation; China's national ETS is claimed to be the largest in the world in terms of emissions covered, estimated to cover more than 4 billion tCO_2 and accounting for over 40% of the country's carbon emissions[22]. To date, 28 ETSs are in operation around the world, either at the

[21] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en#:~:text=The%20EU%20ETS%20is%20a,and%20remains%20the%20biggest%20one.
[22] https://icapcarbonaction.com/en/ets/china-national-ets

regional/state, national or sub-continental level[23]. However, as a carbon price-dependent market, it is inherently subject to volatility, but at least in Europe we can observe a significant increase in the carbon price since the COVID crisis, where it has risen from €20 to over €80 per tonne[24]. This price directly determines the efficiency of such a system, but with the energy crisis we can expect that industrial companies will be strongly encouraged either to produce renewable energy, of which geothermal energy is an interesting option, and then avoid CO_2 emissions, or to decarbonize their activity by capturing and storing their CO_2 emissions.

As a general statement for all first-of-a-kind projects, especially those involving the use of the subsurface as in the cases presented in this study, social acceptance has to be considered as a potential issue with possible strong consequences for the feasibility of the project. In order to anticipate and avoid blockages, this aspect should be carefully considered before the pilot phase. However, it is difficult to address this type of issue too early, when projects are still at a conceptual stage and discussions can only be focused on potential generic test cases. What can be done relatively early on, however, is educational material to prepare the ground for future public debates that will present and explain the project when one or more sites have been pre-selected.

The impressive body of research demonstrated by this remarkable literature production confirms that the use of the subsurface is of great interest as a contribution to the decarbonization of industry and energy production. However, for most of the concepts described in this report, additional work is required to increase their TRL, with the primary objective of reaching at least a pilot phase to validate the concept and measure its performance.

As is often said when talking about energy and environmental transitions, adaptability is key. As mentioned above, we then recommend that:

- 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.

With this in mind, we expect that this report will succeed in providing the scientific community with the most comprehensive overview of the state of the art on the prospective integration of geothermal energy combined with CCS, which clearly is a way to explore in any

[23] https://icapcarbonaction.com/en/ets
[24] https://icapcarbonaction.com/en/ets-prices

decarbonization strategy. We also hope that this material will be useful to stakeholders involved in the energy and environmental transition, in particular regulators and policymakers, who will have a key role to play in making this transition a reality in the relatively short timeframe imposed by the climate emergency.

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8 Appendix

Appendix 8.1 - Spreadsheet Tables[1]

8.1.1 Table 1: Use of supercritical CO_2 as a heat vector for geothermal exploitation and/or energy storage

a. (CPG; CO_2-EGS; Heat mining with SC-CO_2 in gas/oil reservoirs)

b. (CPG-ES, Earth Battery - CO_2-BES/TES)

[1] Upon request to IEAGHG and depending on the circumstances, the original Excel file could be made available to those interested.

SHORT TITLES		Chapter 3.1.1 CPG		Chapter 3.1.2 CO2-EGS		Chapter 3.1.3 Heat mining with SC-CO2 in gas/oil reservoir
AMBITIONS & REPLICABILITY	4,3		3,3		2,5	
► Contribution to energy supply and environmental challenges raised by climate change, i.e. decarbonation through: **- renewable energy production** **- CO2 storage** **- energy storage**	4	► Environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO_2 from an external emitter.	4	► Environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO_2 from an external emitter.	4	► Environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO_2 from an external emitter.
► Replicability (considering the underground conditions)	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 CO_2 makes it possible to extend the potential of water-driven geothermal systems, targeting lower permeability reservoirs. ► The fate of CO_2 and guaranteed containment should be considered with caution and could limit replicability.	3	► The targeted geology is little demanding and the concept could be easily replicated. No water ressource is required. The mobility of CO_2 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 proof of technical feasibility. ► The fate of CO_2 and guaranteed containment should be considered with caution and could limit replicability.	2	► The concept targets former oil/gas reservoirs, especially those exploited with CO2-EOR or CO2-EGR. Replicability is limited to former oil/gas reservoirs with suitable infrastructures.
► Worldwide potential for energy production (individual potential x replicability potential)	4	► A single plant produces several MWe (1-6) with a doublet.	3	► A single plant produces several (5-15) MWe with a doublet	1	► A single plant produces a few MWe with a doublet during a limited duration (~10 years).
► Worldwide potential for CO2 storage (individual potential x replicability potential)	5	► A single plant can store large quantities of CO_2 from an external source, considering the generally high porosity of targeted aquifers.	3	► A single plant can store a significant quantity of CO_2 from an external source (2-15 Mt over 30 years), even if low porosity limits the storage potential in most geological contexts.	3	► The natural gas/oil depletion releases space that can be occupied by CO_2. ► Natural gas reservoirs have proven traps and sealing caprocks that prevent lateral and upward escape of the gas in place, as demonstrated by the long-term accumulation of natural gas in the reservoirs.
INTEGRATION, MODULARITY & SCALABILITY	3,0		3,3		4,0	
► 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?	2	► The range of external CO_2 flux is compatible with volumes produced by large/medium CO_2 emitters. ► Integration with local CO_2 supply should be considered. Transportation of CO_2 penalizes the economic and environmental performance. ► The concept requires a largely higher flow during the initialization phase, which could be a hurdle for integration.	3	► The range of external CO_2 flux is compatible with volumes produced by medium CO_2 emitters. ► Integration with local CO_2 supply should be considered. Transportation of CO_2 penalizes the economic and environmental performance. ► The concept might require a variable flow during the initialization phase, which could be a hurdle for integration.	4	► The range of external CO_2 flux is compatible with volumes produced by large/medium CO_2 emitters. ► Integration is likely to be already in place for CO2-EOR/EGR. ► The concept might require a higher flow during the pressure recovery phase, which could be a hurdle for integration.
► 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?	5	► The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs.	5	► The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs.	5	► The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs.
► Scalability and adaptability **► Modularity and "Plug&play declination"**	2	► The number, depth and design of wells offer adaptability. However, considering implementation complexity, the concept is only viable for large-scale plants. ► The high level of expertise and lack of data for great depths prevent envisaging a plug&play system in the short term.	2	► The number, depth and design of wells offer adaptability. However, considering implementation complexity, the concept is only viable for large-scale plants. ► The high level of expertise and lack of data for great depths prevent envisaging a plug&play system in the short term.	3	► The concept needs to be adapted to the characteristics of each site. The concept is scalable, consideing the oil/gas recovery layout. ► Using/sharing of already-existing multidisciplinary datasets (on reservoir parameters) and infrastructure (surface installations, wells etc.) facilitates implementation.
PERCEPTION BY STAKEHOLDERS	3		2		4	
► Legitimacy of the concept	3	► Socio-political perception of hybrid concepts is ill-known and difficult to predict.	2	► Socio-political perception of hybrid concepts is ill-known and difficult to predict. ► Stimulation is perceived very negatively in some countries.	4	► CO2-EOR and CO2-EGR are already commonly deployed. Adjunction of heat mining introduces limited supplementary features.
READINESS	3		2		4	
► Proof of performance and of safety	3	► The concept is a hybridization of hydrothermal geothermal exploitation and CCS. Both technologies have relatively high TRL. The combination of both concepts should thus be accessible. However, a number of specific technical issues and the design raise specific questions that should be addressed.	2	► Water-driven EGS still encounters numerous technical challenges (deep drilling, stimulation, seismicity). A fortiori, readiness for CO2-EGS is low (CO_2 interactions, CO2-compatible materials considering corrosive features of humid CO_2, etc.)	4	► CO2-EOR and CO2-EGR are already commonly deployed. Hybridization for geothermal energy production introduces new challenges, but readiness can nevertheless be considered as relatively high. Performance is not yet proven, but safety can be considered covered for CO2-EOR/EGR.
ENVIRONMENTAL RISKS & IMPACTS	3,8		3,0		4,3	
► Surface footprint	5	► Surface occupation limited.	5	► Surface occupation limited.	5	► Surface occupation limited.
► Water consumption	4	► Limited water consumption	4	► Water-driven EGS requires an external water resource. Whereas loss of water in a "conventional" (water-driven) EGS operation would be disadvantageous and costly, fluid loss in an EGS system running with CO_2 would offer the possibility of geologically storing CO_2. ► Water required only for drilling and possibly for stimulation.	4	► Limited water consumption
► Guarantee of CO2 containment and safety issues	3	► Containment of supercritical CO_2 in the formation is paid little attention in the state of the art on CPG. It should be thoroughly addressed in order to demonstrate feasibility. Learnings from CCS can easily be used.	1	► Containment of lost CO_2 in the formation is paid very little attention in the literature, but should be thoroughly addressed in order to demonstrate feasibility. The fractured medium is likely to be a challenge for guaranteed containment.	5	► Natural gas reservoirs have proven traps and sealing caprocks that prevent lateral and upward escape of the gas in place, which led to the long-term accumulation of natural gas in the reservoirs.
► Seismic risk (whether natural or controlled)	3	► Seismic risk is generally lower for hydrothermal geothermal than for EGS. The consequences of using CO_2 instead of brine should be verified.	2	► Seismic risk is an important hurdle for wide deployment of EGS. Very little attention until now has been paid to the consequences of using CO_2 instead of brine.	3	► The effects of pressure variations (depletion, pressure recovery, exploitation) should be considered with caution.
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	3,0		1,0		3,0	
► Engineered technical complexity	3	► Drillings: intermediate depth, number of wells limited, suitable design for supercritical CO_2, suitable design for high temperature, suitability of vertical wells. ► No stimulation required in most cases ► CO_2 supply from an external supplyer: requires capture and transport ► Electricity and/or co-generation production requires specific surface installations (either a CO2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid and e.g. ORC turbine) ► Risk of leakage should be monitored and managed.	1	► Drillings: great depth, number of wells limited, suitable design for supercritical CO_2, suitable design for high temperature, suitability of vertical wells. ► Stimulation required in most cases ► CO_2 supply from an external supplyer: requires capture and transport ► Electricity and/or co-generation production requires specific surface installations (either a CO2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid and e.g. ORC turbine) ► Seismic risk should be managed by continuous monitoring and adjustment of injection rates in most cases. Risk of leakage should be monitored and managed.	4	► Most infrastructure already in place (CO_2 supply for CO2-EOR or CO2-EGR, wells). ► Drillings: intermediate depth, number of wells limited, suitable design for supercritical CO_2, suitable design for high temperature ► No stimulation required in most cases ► CO_2 supply from an external supplyer: requires capture and transport ► Electricity and/or co-generation production requires specific surface installations (either a CO2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid and e.g. ORC turbine)
► Degree of i) understanding of thermo-hydro-mechanical and microbio-geochemical phenomena and ii) management of the underground technical design	3	► A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling. ► The system involves several phases (water-phase, CO2-phase). ► Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields have already addressed some of these.	1	► The level of random and epistemic uncertainty is high considering the great depth. ► The concept targets fractured reservoirs, which adds some complexity for modelling. ► The system involves several phases (water-phase, CO2-phase). ► An important challenge is to do THM modelling in order to anticipate seismic issues. ► A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling. Thermo-hydro-mechanical 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).	2	► The level of uncertainty is moderate considering the knowledge already aquired during former exploitation. ► The system involves several phases (water-phase, CO2-phase, oil or gas phase). ► A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling.
CREDIBLE PATH TO COMMERCIALITY	3,0		1,5		4,5	
► Development risks	3	► Development risks are moderate for hydrothermal geothermal exploitation to date considering underground uncertainties and management of technical issues (injectivity, productivity, clogging, etc.). ► Operating with CO_2 instead of water adds additional uncertainty at the moment, but after more experience feedback, using CO_2 could limit the development risks (higher mobility and lower dissolution).	1	► Development risks are important to date considering the high level of underground uncertainties before drilling, drilling complexity at depth, management of permeability, stimulation and fluid circulation and management of seismic risk. ► Operating with CO_2 instead of water adds additional uncertainty and development risk in the current state of knowledge, but after more experience feedback, using CO_2 could limit development risks (higher mobility and lower dissolution).	4	► Main development risks are taken by oil/gas exploitation.
► Investment costs **► Economic performance**	3	► Investment costs are important considering moderate drilling depth and surface installations for CO_2 capture and supply ► The initialization period is relatively long (porosity limited). ► The engineering choices should be properly designed and adjusted to avoid decrease of heat recovery with time. ► The business model benefits from a double source of revenue (energy and CCS, with high CO_2 storage quantities involved)	2	► Investment costs are very important considering high drilling depth, stimulations, and surface installations for CO_2 capture and supply ► The initialization period is relatively short (porosity limited). ► The choice of engineering design to have good circulation and no thermal breakthrough is a challenge. ► The business model benefits from a double source of revenue (energy and CCS)	5	► Economic benefits are achieved by using/sharing already-existing data (on reservoir parameters) and infrastructure (surface facilities, wells etc.). Hence, investment costs are significantly reduced. ► The engineering choices should be properly designed and adjusted to avoid decrease of heat recovery with time. The exploitation duration is generally limited (~10 years). ► The business model benefits from a double source of revenue (energy and CCS, with high CO_2 storage quantities involved)

SHORT TITLES	Chapter 3.1.4.1 CPG-ES		Chapter 3.1.4.2 Earth Battery - CO2-BES/TES	
AMBITIONS & REPLICABILITY	**3,8**		**4,5**	
▶ Contribution to energy supply and environmental challenges raised by climate change, i.e. decarbonation through: **- renewable energy production** **- CO2 storage** **- energy storage**	**5**	▶Environmental and energetic performances become outstanding by combining non-intermittent renewable energy production, electricity storage and CO2 storage from an external emitter.	**5**	▶The environmental and energetic performances become outstanding by combining non-intermittent renewable energy production, electricity storage and CO2 storage from an external emitter.
▶ Replicability **(considering the underground conditions)**	**3**	▶ The targeted geology requires two porous and permeable aquifers, located at similar locations, with two efficient caprocks. The fate of CO2 and guaranteed containment should be considered with caution and could limit replicability. ▶ The mobility of CO2 makes it possible to extend the potential of water-driven geothermal systems, targeting lower permeability reservoirs.	**3**	▶ The targeted geology requires a very large porous and permeable aquifer, overlain by an efficient caprock. The fate of CO2 and guaranteed containment should be considered with caution and could limit replicability. ▶ The mobility of CO2 makes it possible to extend the potential of water-driven geothermal systems, targeting lower permeability reservoirs
▶ Worldwide potential for energy production **(individual potential x replicability potential)**	**3**	▶ A single plant produces several MWe with a doublet.	**5**	▶ A single plant produces several hundreds of MWe.
▶ Worldwide potential for CO2 storage **(individual potential x replicability potential)**	**4**	▶ A single plant can storelarge quantities of CO2 from external sources.	**5**	▶ A single plant can stores large quantities of CO2 from external sources.
INTEGRATION, MODULARITY & SCALABILITY	**2,7**		**3,0**	
▶ 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?	**2**	▶The range of external CO2 flux is compatible with volumes produced by large/medium CO2 emitters. ▶ Integration with local CO2 supply should be considered. Transportation of CO2 penalizes the economic and environmental performance. ▶ The concept requires a largely higher flow during the initialization phase, which could be a hurdle for integration.	**4**	▶The range of external CO2 flux is compatible with volumes produced by large/medium CO2 emitters. ▶ Integration with local CO2 supply should be considered. Transportation of CO2 penalizes the economic and environmental performance.
▶ 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?	**4**	▶ The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs. ▶ The technology also delivers electricity services storage, which requires more complexity for integration in the grid than electricity production only.	**4**	▶ The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs. ▶ The technology also delivers electricity services storage, which requires more complexity for integration in the grid than electricity production only.
▶ Scalability and adaptability **▶ Modularity and "Plug&play declination"**	**2**	▶The number, depth and design of wells offer adaptability. However, considering implementation complexity, the concept is only viable for large-scale plants. ▶ The high level of expertise and lack of data for great depths prevent envisaging a plug&play system in the short term.	**1**	▶The number, depth and design of wells offer adaptability. However, considering implementation complexity, the concept is only viable for very large-scale plants. ▶ The high level of expertise and lack of data for great depths prevent envisaging a plug&play system in the short term.
PERCEPTION BY STAKEHOLDERS	3		3	
▶ Legitimacy of the concept	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict.	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict.
READINESS	2		2	
▶ Proof of performance and of safety	**2**	▶The concept is a hybridization of hydrothermal geothermal exploitation, electricity storage and CCS. CCS and geothermal heat extraction have relatively high TRL. However, the combination has not been demonstrated. Adjunction of the energy storage component and the layout with rings (achieved with horizontal wells) raises a number of specific technical issues. The hybrid design raises specific questions that should be addressed.	**2**	▶The concept is a hybridization of hydrothermal geothermal exploitation, electricity storage, compressed CO2 energy storage and CCS. CCS and geothermal heat extraction have relatively high TRL. However, the combination has not been demonstrated. Adjunction of the energy storage component and the layout with rings (achieved with horizontal wells) raises a number of specific technical issues. The hybrid design raises specific questions that should be addressed.
ENVIRONMENTAL RISKS & IMPACTS	**3,5**		**3,5**	
▶ Surface footprint	**5**	▶Surface occupation limited.	**4**	▶Surface occupation is moderate (surface tank to store brine during discharge period).
▶ Water consumption	**4**	▶Limited water consumption	**4**	▶Limited water consumption
▶ Guarantee of CO2 containment and safety issues	**2**	▶ Containment of supercritical CO2 in both formations raises significant issues. Learnings from CCS can be used.	**3**	▶ Containment of lost CO2 in the formation raises significant issues. Learnings from CCS can be used.
▶ Seismic risk (whether natural or controlled)	**3**	▶ Seismic risk is generally lower for hydrothermal geothermal than for EGS. The consequences of using CO2 instead of brine should be verified.	**3**	▶ Seismic risk is generally lower for hydrothermal geothermal than for EGS. The consequences of using CO2 instead of brine should be verified.
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	**2,5**		**2,5**	
▶ Engineered technical complexity	**2**	▶ Drillings: intermediate depth, several wells required - at least 6-, suitable design for supercritical CO2, suitable design for high temperature, use of horizontal wells is favoured. ▶ No stimulation required in most cases ▶ CO2 supply from an external supplyer: requires capture and transport ▶ Electricity and/or co-generation production requires specific surface installations (either a CO2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid and e.g. ORC turbine). Cycles of injection and production in shallower aquifers and integration with the electricity network balance requirements (balance supply/demand) raise a supplementary complexity. ▶ Risk of leakage should be monitored and managed.	**2**	▶ Drillings: intermediate depth, tens of wells, suitable design for supercritical CO2, suitable design for high temperature. ▶ No stimulation required in most cases ▶ CO2 supply from an external supplyer: requires capture and transport ▶ Electricity and/or co-generation production with CO2 and brine (and mixed fluid) requires specific surface installations. A surface tank is required for brine storage. Cycles of injection and production in shallower aquifers and integration with the electricity network balance requirements (balance supply/demand) raise a supplementary complexity. ▶ Risk of leakage should be monitored and managed.
▶ Degree of i) understanding of thermo-hydro-mechanical and microbio-geochemical phenomena and ii) management of the underground technical design	**3**	▶ There is high temperature difference between the fluid produced and the reinjection temperature, which is a challenge for THM -CB modelling. ▶ The system involves several phases (water-phase, CO2-phase). ▶ Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some challenges.	**3**	▶ There is high temperature difference between the fluid produced and the reinjection temperature, which is a challenge for THM -CB modelling. ▶ The system involves several phases (water-phase, CO2-phase). ▶ Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some challenges.
CREDIBLE PATH TO COMMERCIALITY	**2,0**		**2,5**	
▶ Development risks	**2**	▶ Operating with CO2 instead of water adds additional uncertainty at the moment, but after more experience feedback, using CO2 could limit development risks (higher mobility and lower dissolution). ▶ Drilling depth is moderate but the number of wells or the necessity for horizontal wells is a challenge. ▶ The necessity of two aquifers with suitable characteristics increases the level of risk.	**2**	▶ Operating with CO2 instead of water adds additional uncertainty at the moment, but after more experience feedback, using CO2 could limit development risks (higher mobility and lower dissolution). ▶ Drilling depth is moderate but the number of wells or the necessity for horizontal wells is a challenge. ▶ The necessity to reach high-scale operations in order to have a functional Earth Battery increases the level of risk.
▶ Investment costs **▶ Economic performance**	**2**	▶ Investment costs are important considering horizontal wells, number of wells and surface installations, ▶ The initialization period is relatively long (2.5 years) ▶ The engineering choices should be properly designed and adjusted to avoid decrease of heat recovery with time. ▶ The business model benefits from a triple source of revenue (electricity supply, electricity storage, and CCS, with high CO2 storage quantities involved)	**3**	▶ Investment costs are important considering the number of wells and surface installations, ▶ Limited initialization ▶ The management of such complex system is delicate. Engineering choices should be well-designed and adjusted to guarantee performance over time. ▶ The business model benefits from a triple source of revenue (electricity supply, electricity storage, and CCS, with high CO2 storage quantities involved)

8.1.2 Table 2:
a. Water-driven geothermal heat extraction with CO_2 injection to achieve near-zero CO_2 geothermal production (Carbfix-like concept; CO_2-reinjection concept; CLEAG-like concept)
b. Water-driven geothermal heat extraction with CO_2 injection of CO_2 in dissolved form for CCS (CO_2-DISSOLVED-like concept; Geothermal BECCS; CCS driven concept)

		Chapter 3.2.2		Chapter 3.2.3		Chapter 3.2.4
SHORT TITLES		Carbfix*-like concept		CO_2-reinjection concept		CLEAG-like concept
		*: we focus only on a specific application of the concept, when coupled with geothermal energy extraction, with reinjection of the CO_2 naturally produced with the geothermal fluid.				
AMBITIONS & REPLICABILITY	2,5		3,5		3,0	
► Contribution to energy supply and environmental challenges raised by climate change, i.e. decarbonation through: **- renewable energy production** **- CO_2 storage** **- energy storage**	2	► Pairing geothermal heat extraction and storage with the Carbfix concept leads to non-intermittent large-scale renewable energy production with limited emissions, which is a strong contribution to climate-change challenges, even without CO_2 storage from an external source.	2	► Producing non-intermittent geothermal heat energy with nearly-zero emissions is a strong contribution to energy supply and environmental challenges, even without CO_2 storage from an external source.	3	►Environmental and energetic performances are high by combining non-intermittent geothermal energy production, fully utilizing the geothermal hot brine content (heat and combustible gases) with near-zero emissions. No CO_2 from an external source is stored, but both naturally produced CO_2 and CO_2 from combustion are stored.
► Replicability **(considering the underground conditions)**	2	► Pairing geothermal heat extraction with the CarbFix storage concept is restricted to very specific geological contexts highly reactive rocks such as basalts and geothermal fluids that contain NCG. ►NB: In-situ mineralization offers a large potential volume for carbon storage in formations such as basalts and peridotites (both onshore and offshore). The CarbFix storage concept can be deployed with CO_2 from any other external source (in this case it is not a hybrid-concept any more). In the present study, we focus on the hybridization between geothermal extraction and CO_2 storage, not on the CarbFix concept as a whole.	4	►Geothermal worldwide potential is high. The NCG-reinjection concepts could be deployed for all power plants that present non-negligible NCG content. Reinjection is overriding for geothermal exploitation in some specific geological contexts with very high NCG content (Italy, Turkey).	3	►The concept requires specific geological features, notably a geothermal fluid with significant methane content. Extensively researched oil and gas watered fields around the globe possess similar characteristics,thus corresponding to a well-known replicability potential. According to the CLEAG project team, replicability is promising, especially in Eastern Europe where many existing wells are present. These oil&gas wells could be retrofitted for geothermal use.
► Worldwide potential for energy production **(individual potential x replicability potential)**	4	►The energy production potential of an individual site is high (hundreds of MWe).	5	►The energy production potential of an individual site is high (hundreds of MWe).	4	►A single plant produces tens of MWe and MWth with limited number of wells.
► Worldwide potential for CO_2 storage **(individual potential x replicability potential)**	2	► The storage potential for the CarbFix concept paired with geothermal heat extraction is limited by the CO_2 content of the geotherma fluid rather than by the underground potential. Potential could be improved by injection of external CO_2. ► No storage from an external source	3	► The NCG-reduction potential is directly related to the NCG content, by comparison with current practices (very high in Italian and Turkish contexts for instance). ► No storage from an external source	2	► The NCG-reduction potential is directly related to the NCG content, by comparison with current practices. ► No storage from an external source
INTEGRATION, MODULARITY & SCALABILITY	4,3		3,7		4,0	
► Upstream requirements: does the concept require an external supply (e.g. CO_2)?; are the quantitative and qualitative requirements realistic and are they compatible with the overall system?	4	NA	3	NA	3	NA
► 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?	5	► The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs.	5	► The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. Valorization of co-produced heat should be considered regarding local needs.	4	► The technology delivers between other non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. ► The technology delivers heat that should correspond to local needs. The level of heat production is around a few MWth. This order of magnitude might coincide with various possible uses at local scales (DHN, industries, etc.).
► Scalability and adaptability **► Modularity and "Plug&play declination"**	4	►The number, depth and design of wells offer adaptability. The concept has already been deployed for several demonstrators and is thus proven to be modular, adaptable and scalable.	3	►As illustrated by the variety of demonstrators, the concept is scalable. ► Modularity is however limited, each context (geolgical and surface installations) requires specific adaptation.	5	►The concept is conceived with plug&play modular design that allows great flexibility, adaptable to local geology.
PERCEPTION BY STAKEHOLDERS	5		4		5	
► Legitimacy of the concept	5	►The concept has already been deployed in the Icelandic context.	4	►The concept involves minor changes compared to an existing geothermal power plant.	5	►The concept is currently deployed in Croatia. It involves minor changes compared to an existing geothermal power plant.
READINESS	5		3		5	
► Proof of performance and of safety	5	►The concept has already been demonstrated since 2014 at industrial scale.	3	►Partial reinjection has already been proven. The technical challenges raised by injection in the dissolved form can technically be addressed, as demonstrated within the CarbFix project. ► Reinjection in supercritical form or as a liquid mixture for geothermal fields with high NCG raises more technical challenges.	5	►The concept has already been demonstrated since 2014 at industrial scale.
ENVIRONMENTAL RISKS & IMPACTS	4,3		4,3		4,3	
► Surface footprint	5	►Surface occupation limited.	5	►Surface occupation limited.	5	►Surface occupation limited.
► Water consumption	4	►Limited water consumption	4	►Limited water consumption	4	►Limited water consumption
► Guarantee of CO_2 containment and safety issues	5	►In-situ mineralization results in a negligible risk of leakage both over the short term (due to the dissolution of CO_2 and the density-related inhibition of surface migration) and the long term (due to conversion into carbonate minerals).	4	►If the CO_2 is injected and remains in dissolved form, no light gaseous or supercritical phase is involved and the risk of leakage is limited. ► If the CO_2 is injected in supercritical or liquid form, containment in the geothermal reservoir should be thoroughly addressed.	4	►The CO_2 is injected in dissolved form, no light gaseous or supercritical phase is involved and the risk of leakage is limited.
► Seismic risk (whether natural or controlled)	3	► Seismic risk is managed by continuous monitoring and adjustment of injection rates. Concerning proof of concept, it has been demonstrated that seismicity is an issue that can be managed.	4	► From a thermo-hydro-mechanical point of view, the concept involves minor changes compared to an existing geothermal power plant. The consequences of CO_2 reinjection should nevertheless be verified.	4	► From a thermo-hydro-mechanical point of view, the concept involves minor changes compared to an existing geothermal power plant. The consequences of CO_2 reinjection should nevertheless be verified.
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	4,0		3,5		4,5	
► Engineered technical complexity	4	► Drillings: intermediate depth, number of wells limited, suitable design for geothermal fluid containing dissolved CO_2, suitable design for high temperature, suitability of vertical wells. ► No stimulation required ► CO_2/other NCG from the geothermal fluid: requires specific surface installations to process the fluid (e.g. separator/scrubber, compressor) ► Electricity and/or co-generation production requires specific surface installations (either a CO_2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid and e.g. ORC turbine) ► Seismic risk should be managed by continuous monitoring and adjustment of the injection rates in most cases ► Technical complexity can be overcome, as demonstrated on the Icelandic pilot and demonstrator	4	► Drillings: intermediate depth, number of wells limited, suitable design for liquid/supercritical CO_2 injection in 1 well, suitable design for high temperature, suitability of vertical wells. ► No stimulation required ► CO_2/other NCG from the geothermal fluid: requires specific surface installations to process the fluid (e.g. separator/scrubber, compressor) ► Electricity and/or co-generation production requires specific surface installations (either a CO_2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid and e.g. ORC turbine) ► Risk of leakage should be monitored and managed if injection is done in the supercritical/liquid phase. ► Technical complexity can be overcome; it is currently being validated on the Turkish demonstrator.	5	► Drillings: moderate depth, number of wells limited, suitable design for dissolved CO_2 injection, temperature requirement <100°C, suitability of vertical wells. ► No stimulation required ► CH_4/CO_2/other NCG from the geothermal fluid: requires specific surface installations to process the fluid (e.g. separator/scrubber, compressor) ► Electricity and/or co-generation production requires specific surface installations for geothermal fluid exploitation (either a CO_2-compatible turbine, or binary cycle power system - with heat exchanger, secondary fluid (and e.g. ORC turbine) and for methane exploitation (gas turbine) ► Technical complexity can be overcome, as demonstrated on the Croatia demonstrator
► Degree of i) understanding of thermo-hydro-mechanical and microbio-geochemical phenomena and ii) management of the underground technical design	4	► The concept could target heterogenous reservoirs. ► A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling. ► Numerous geochemical studies are required to understand and manage geochemical reactions, their kinetics and localization in the well, already well studied within the CarbFix project.	3	►CO_2 injection in the supercritical/liquid phase raises specific challenges that complexify the work. In most cases, it is planned to inject CO_2 in dissolved form. ► A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling. ► Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some of these.	4	►The thermo-hydro-mechanical understanding, modelling and management at such depths and temperatures in permeable aquifers represent moderate challenges. The addition of CO_2 in dissolved form could induce minor changes that have been addressed in the CO_2-Dissolved project. ► Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some of these.
CREDIBLE PATH TO COMMERCIALITY	4,0		3,0		4,0	
► Development risks	4	► Development risks are limited for well-known geothermal reservoir in fields already exploited and characterized (Iceland) ► Adjunction of the capture and reinjection components adds a moderate development risk considering the additional technical challenges and uncertainties for near-well behaviour in the reinjection well.	3	►Development risks are limited for well-known geothermal reservoirs in fields already exploited and characterized (Turkey, Italy), but might remain significant for great depths or new geothermal fields. ► Adjunction of the capture and reinjection components add a moderate development risk considering the additional technical challenges and uncertainties for near-well behaviour in the reinjection well.	4	►The technology requires a fluid T less than 100-120 °C, it targets limited depth and well-known aquifers, which substantially decreases development risk ► Adjunction of the capture and reinjection components adds a moderate development risk considering the additional technical challenges and uncertainties for near-well behaviour in the reinjection well.
► Investment costs **► Economic performance**	4	► Investment costs are moderate considering moderate drilling depth, surface installations for gas separation and reinjection. ► No initialization phase ► The energy production performance in suitable contexts has already been demonstrated over years. It is not penalized by NCG reinjection according to results available for the demonstrator in operation since 2014. ► The business model relies on energy revenue. When the cost of CO_2 emitting will be more in line with environmental challenges, the competitiveness of the concept will be improved, since the energy revenue will not be penalized by emissions penalties.	3	► Investment costs are moderate to high, depending on drilling depths and surface installations for gas separation and reinjection. ► No initialization phase ► The geothermal energy production performance in suitable contexts has already been demonstrated over years. The consequences of reinjection on efficiency performance and robustness are expected to be low, but have not been demonstrated over years. ► The business model relies on energy revenue alone. When the cost of CO_2 emitting will be more in line with environmental challenges, the competitiveness of the concept will be improved, since the energy revenue will not be penalized by emissions penalties.	4	► Investment costs are moderate (moderate drilling depth, surface installations for gas capture and reinjection, gas turbine) ► No initialization phase ► The energy production performance in suitable contexts has already been demonstrated over years. It is not penalized by NCG reinjection according to results available for the demonstrator in operation since 2014. ► The business model relies on energy revenue alone. When the cost of CO_2 emitting will be more in line with environmental challenges, the competitiveness of the concept will be improved, since the energy revenue will not be penalized by emissions penalties.

	Chapter 3.2.5		Chapter 3.2.6.1		Chapter 3.2.6.2	
SHORT TITLES	**CO_2-Dissolved-like concept**		**Geothermal BECCS**		**CCS-driven concept**	
AMBITIONS & REPLICABILITY	**4,0**		**4,8**		**2,8**	
▶ Contribution to energy supply and environmental challenges raised by climate change, i.e. decarbonation through: **- renewable energy production** **- CO_2 storage** **- energy storage**	**3**	▶ Environmental and energetic performances are high by combining non-intermittent renewable energy production and storage of CO_2 from an external emitter. The amount of CO_2 that can be stored is limited by the solubility limit.	**4**	▶Environmental and energetic performances are very high, by combining non-intermittent renewable energy production from two sources (bioenergy and geothermal energy) and CO_2 storage from biomass.	**2**	▶Performances are higher, compared to a conventional CCS power plant, by utilizing geothermal energy production to avoid energy penalties due to capture. The concept fully utilizes the geothermal hot brine content (heat and combustible gases). ▶ CO_2 from combustion is emitted but not stored.
▶ Replicability **(considering the underground conditions)**	**5**	▶ Resource potential for medium-temperature geothermal extraction worldwide is high.	**5**	▶ Resource potential for medium-temperature geothermal extraction worldwide is high.	**2**	▶The concept requires specific geological features, notably a geothermal fluid with significant methane content. The concept requires a large suitable aquifer considering the large volumes involved.
▶ Worldwide potential for energy production **(individual potential x replicability potential)**	**4**	▶A single plant produces a few MWth with a doublet.	**5**	▶A single plant could produce several tens of MWe with a limited number of wells. The contrbution of geothermal energy to this production is not explicitly mentioned, but it can be considered to be around 20-50%.	**3**	▶The energy production potential of an individual site is high (hundreds of MWe), but mainly for internal processes.
▶ Worldwide potential for CO_2 storage **(individual potential x replicability potential)**	**4**	▶A single plant could store a significant quantity of CO_2 (a few Mt over 30 years).	**5**	▶A single plant could store a significant quantity of CO_2 (around 10 Mt over 30 years).	**4**	▶ A single plant can store large quantities of CO_2 from external sources.
INTEGRATION, MODULARITY & SCALABILITY	**4,0**		**4,3**		**3,7**	
▶ Upstream requirements: does the concept require an external supply (e.g. CO_2)?; are the quantitative and qualitative requirements realistic and are they compatible with the overall system?	**5**	▶The concept is adapted to small CO_2 industrial emitters (<150,000 t/year), which is the case for the majority of emitters (in terms of number). ▶ The system can work with any CO_2 capture technology but the aqueous 'Pi-CO2' capture technology (PI-Innovation, Inc., USA) is preferential as it outputs carbonated water (rather than gaseous CO_2) that makes CO_2 injection more efficient.	**4**	▶The design of the concept takes into account the biomass power plant, carbon storage and geothermal energy production as a holistic system. The only requirement is the availability of a suitable reservoir and a biomass resource. ▶ Proximity to sustainable biomass fuel source could be a limiting factor for geothermal-BECCS deployment.	**4**	▶The range of external CO_2 flux is compatible with volumes produced by large CO_2 emitters. ▶ Integration with local CO_2 supply should be considered. Transportation of CO_2 penalizes the economic and environmental performance.
▶ 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?	**3**	▶ The technology delivers heat that should correspond to local needs. The level of heat production is around a few MWth. This order of magnitude might coincide with various possible uses at local scales (DHN, industries, etc.).	**5**	▶ Geothermal energy extraction produces heat. The heat is used for water pre-heating in the biomass power plant. The technology delivers notably non-intermittent renewable electricity, which can easily be valorized considering current energy challenges. It should be noted that possible valorization of co-produced heat (if any) should be considered regarding local needs.	**4**	▶ The technology delivers notably heat. The heat is used for local needs already well-identified (CO_2 capture process).
▶ Scalability and adaptability **▶ Modularity and "Plug&play declination"**	**4**	▶The concept is conceived with modular design. ▶ The concept targets a specific scale (small emitters and heat production through a doublet). The number of doublets can be adapted if necessary.	**4**	▶Although not yet demonstrated, the concept should be modular, with the possibility to adjust the number of wells, the size of the biomass power plant, the energetic systems to work with various geothermal temperatures.	**3**	▶The CCS objectives demand a large scale of the technology. Scalability and adaptibility are limited.
PERCEPTION BY STAKEHOLDERS	3		3		3	
▶ Legitimacy of the concept	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict. However, public perception of geothermal heat production is generally positive.	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict.	3	▶ Socio-political perception of CCS is a challenge. Adjunction of the CCS component might be marginal for perception since the main system remains CCS.
READINESS	4		3		2	
▶ Proof of performance and of safety	**4**	▶ The concept is almost ready to move to an industrial-scale demonstrator. It relies on the assembly of different components that can be individually considered as mature.	**3**	▶Technico-economic feasibility has not been demonstrated. ▶ However, it relies on the assembly of different components that can be considered as mature.	**2**	▶CCS has already been demonstrated, but in supercritical state and without the geothermal component ▶ The concept raises some feasibility questions: - the CO_2 will probably reach the production well after some years; it can be reinjected, but it will limit the quantity of additional external CO_2 that can be dissolved; - the methane content might decrease over time; - the required volume of CO_2 in dissolved form is high (a reason for CO_2 storage in the supercritical form is related to the high supecritical density).
ENVIRONMENTAL RISKS & IMPACTS	**4,3**		**4,0**		**4,0**	
▶ Surface footprint	**5**	▶Surface occupation limited. The space requirement for the capture operations is dependant on the technology used.	**4**	▶Surface occupation limited. The biomass power plant and biomass supply might require some additional surface.	**5**	▶Surface occupation limited.
▶ Water consumption	**4**	▶Limited water consumption (water requirements are supplied by the geothermal fluid)	**4**	▶Limited water consumption	**4**	▶Limited water consumption
▶ Guarantee of CO_2 containment and safety issues	**4**	▶The CO_2 is injected in dissolved form, no light gaseous or supercritical phase is involved and the risk of leakage is limited.	**4**	▶The CO_2 is injected in dissolved form, no light gaseous or supercritical phase is involved and the risk of leakage is limited.	**4**	▶The CO_2 is injected in dissolved form, no light gaseous or supercritical phase is involved and the risk of leakage is limited.
▶ Seismic risk (whether natural or controlled)	**4**	▶ From a thermo-hydro-mechanical point of view, the concept involves minor changes compared to an existing geothermal power plant. The consequences of CO_2 reinjection is anticipated to be minimal but should nevertheless be verified.	**4**	▶ From a thermo-hydro-mechanical point of view, the concept involves minor changes compared to an existing geothermal power plant. The consequences of CO_2 reinjection should nevertheless be verified.	**3**	▶ Seismic risk should be considered, as for any CCS or storage/exploitation involving large volumes.
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	**4,5**		**3,5**		**3,5**	
▶ Engineered technical complexity	**5**	▶ Drillings: moderate depth, number of wells limited, suitable completion design for dissolved CO_2 injection (fiberglass casing), temperature requirement <100°C, suitability of deviated wells, but the technology is well known and mature. ▶ No stimulation required ▶ CO_2 supply from an external supplier: requires a capture unit (and sometimes transport) ▶ Thermal energy production exploitation requires specific surface installations (heat exchanger with secondary fluid) connected to the final end users (e.g. District Heating Network, industrial heat-supply network).	**4**	▶ Drillings: moderate depth, number of wells limited, suitable design for dissolved CO_2 injection, temperature requirement <100°C, suitability of vertical wells. ▶ No stimulation required ▶ Complexity of integration with synergetic use of geothermal energy and biomass energy.	**4**	▶ Drillings: moderate depth, high number of wells, suitable design for dissolved CO_2 injection, temperature requirement around 150°C. ▶ No stimulation required ▶ CH_4 from the geothermal fluid: requires specific surface installations to process the fluid (e.g. separator/scrubber, compressor) ▶ Electricity and/or co-generation production requires specific surface installations for geothermal fluid exploitation (either a CO_2-compatible turbine, or binary cycle power system - with a heat exchanger, secondary fluid (and e.g. ORC turbine) and for methane exploitation (gas turbine)
▶ Degree of i) understanding of thermo-hydro-mechanical and microbio-geochemical phenomena and ii) management of the underground technical design	**4**	▶The thermo-hydro-mechanical understanding, modelling and management at such depths and temperatures in permeable aquifers represent moderate challenges. The addition of CO_2 in dissolved form could induce minor changes that have been addressed in the CO2-Dissolved project. ▶ Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some of these.	**3**	▶The thermo-hydro-mechanical understanding, modelling and management at such depths and temperatures in permeable aquifers represent moderate challenges. The addition of CO_2 in dissolved form could induce minor changes that have been addressed in other similar projects (e.g. CO2-Dissolved project). ▶ Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some of these. ▶ A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling.	**3**	▶The thermo-hydro-mechanical understanding, modelling and management in permeable aquifers represent moderate challenges. The addition of CO_2 in dissolved close to the solubility limit represents however an additional challenge (possible free phase creation). ▶ Geochemical understanding, modelling and management still represent challenges, but learnings from geothermal and CCS fields already addressed some of these.
CREDIBLE PATH TO COMMERCIALITY	**4,0**		**4,0**		**2,5**	
▶ Development risks	**4**	▶The technology requires a fluid T less than 100 °C, it targets limited depth and well-known aquifers, which substantially decreases development risk ▶ Adjunction of the capture and reinjection components adds a moderate development risk considering the additional technical challenges and uncertainties for near-well behaviour in the reinjection well.	**4**	▶The technology targets limited depth aquifers, which substantially decreases development risks ▶ Adjunction of the capture and reinjection components adds a moderate development risk considering the additional technical challenges and uncertainties for near-well behaviour in the reinjection well. ▶ Geothermal-BECCS systems could improve the accessibility of the majority of geothermal systems, which are classified as low enthalpy.	**3**	▶ Development risks are still high for CCS exploitation considering underground uncertainties and management of technical issues (injectivity, plume management, leakage risk, geochemistry, etc.). ▶ Operating with pumping and dissolved CO_2 adds additional uncertainty at the moment, but reduces leakage risks.
▶ Investment costs **▶ Economic performance**	**4**	▶ Investment costs are moderate and well known for the geothermal doublet part (intermediate drilling depth, surface installations for gas capture and reinjection). More cost uncertainty remains depending on the capture technology used. OPEX for geothermal heat production and use are well-known. OPEX for CO_2 capture and injection still need to be more precisely assessed by a demonstration facility ▶ No initialization phase needed ▶ The geothermal energy production performance in suitable contexts has already been successfully demonstrated over the years. The consequences of CO_2 injection on efficiency performance and robustness are expected to be low, but have not been demonstrated yet. ▶ The business model benefits from a double source of revenue (energy and CO_2 tax avoidance).	**4**	▶ Investment costs are moderate to high (drilling depth, surface installations for gas capture and reinjection, complexity of the synergetic system) ▶ No initialization phase ▶ The geothermal energy production performance in suitable contexts has already been demonstrated over years. The consequences of reinjection on efficiency performance and robustness are expected to be low, but have not been demonstrated over years. ▶ The business model benefits from a double source of revenue (energy and, to a lesser degree, CCS)	**2**	▶ Investment costs are high. ▶ No initialization phase ▶ The performances over time are debatable (CO_2 breakthrough, decrease of methane content, volume required for storage of large quantities in dissolved form, etc.) ▶ The business model relies on CCS revenue alone.

8.1.3 Table 3: Other synergies (Synergy through pressure management; Synergetic dual use in the same reservoir; Hybrid energy systems; CCS with geothermal energy for capture process)

		Chapter 3.3.1		Chapter 3.3.2		Chapter 3.3.3		Chapter 3.3.4
SHORT TITLES		**Synergy through pressure management**		**Synergetic use through dual uses in the same reservoir**		**Hybrid-energy systems**		**CCS with geothermal energy for capture process**
AMBITIONS & REPLICABILITY	**4,3**		**4,0**		**3,5**		**3,3**	
▶ Contribution to energy supply and environmental challenges raised by climate change, i.e. decarbonation through: **- renewable energy production** **- CO_2 storage** **- energy storage**	**4**	▶Environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO_2 from an external emitter.	**4**	▶Environmental and energetic performances are very high by combining non-intermittent renewable energy production and storage of significant amounts of CO_2 from an external emitter.	**5**	▶ The concept produces geothermal energy and stores CO_2 from fossil/biomass power plant, and proposes storage services (short term and seasonal storage)	**2**	▶ Performances are higher, compared to a conventional CCS power plant, by utilizing geothermal energy production to avoid energy penalties due to capture. ▶ No additional energy production for other uses.
▶ Replicability **(considering the underground conditions)**	**3**	▶ The targeted geology requires a porous and permeable aquifer. These geological features are relatively widespread, but coveted for other uses too. ▶ The fate of CO_2 and guaranteed containment should be considered with caution and could limit replicability. The whole system requires a large suitable aquifer.	**4**	▶ The targeted geology requires a porous and permeable aquifer. These geological features are relatively widespread, but coveted for other uses too. ▶ The fate of CO_2 and guaranteed containment should be considered with caution and could limit replicability.	**2**	▶ The concept requires 2 nearby aquifers. ▶ The concept requires medium temperature (around 90°C) ▶ The system requires water handling (water production in an aquifer and reinjection in a different aquifer)	**3**	▶ The concept targets a CCS power plant with a nearby geothermal resource (thus 2 aquifers).
▶ Worldwide potential for energy production **(individual potential x replicability potential)**	**5**	▶The energy production potential of an individual site corresponds to several hundreds of MWth	**3**	▶The energy production potential of an individual site corresponds to a few MW.	**3**	▶The energy production potential of an individual site is high (hundreds of MWe), but partly from fossil fuel energy.	**3**	▶The energy production potential of an individual site is high (hundreds of MWe), but mainly for internal processes.
▶ Worldwide potential for CO_2 storage **(individual potential x replicability potential)**	**5**	▶ A single plant can store large quantities of CO_2 from external sources.	**5**	▶ A single plant can store large quantities of CO_2 from external sources.	**4**	▶ A single plant can store large quantities of CO_2.	**5**	▶ A single plant can store large quantities of CO_2 from external sources.
INTEGRATION, MODULARITY & SCALABILITY	**3,0**		**3,3**		**4,0**		**3,7**	
▶ Upstream requirements: does the concept require an external supply (e.g. CO_2)?; are the quantitative and qualitative requirements realistic and are they compatible with the overall system?	**4**	▶The range of external CO_2 flux is compatible with volumes produced by medium-large CO_2 emitters. ▶ Integration with local CO_2 supply should be considered. Transportation of CO_2 penalizes the economic and environmental performance.	**4**	▶The range of external CO_2 flux is compatible with volumes produced by medium-large CO_2 emitters. ▶ Integration with local CO_2 supply should be considered. Transportation of CO_2 penalizes the economic and environmental performance.	**5**	▶The design of the concept takes into account the power plant, carbon storage and geothermal energy production as a holistic system. The only requirement is the availability of two suitable reservoirs.	**4**	▶The range of external CO_2 flux is compatible with volumes produced by large CO_2 emitters. ▶ Integration with local CO_2 supply should be considered. Transportation of CO_2 penalizes the economic and environmental performance.
▶ 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?	**2**	▶ The technology delivers heat that should correspond to local needs. The level of heat production is relatively high, which increases the challenges raised by local valorization. ▶ Water disposal in case of partial reinjection might add some technical and regulation difficulty.	**3**	▶ The technology delivers heat that should correspond to local needs. The level of heat production is around a few MWth. This order of magnitude might coincide with various possible uses at local scales (DHN, industries, etc.).	**5**	▶ Geothermal energy extraction produces heat. The heat is used for water pre-heating in the biomass power plant. The technology delivers notably electricity, which can easily be valorized considering current energy challenges.	**4**	▶ The technology delivers notably heat. The heat is used for local need already well-identified (CO_2 capture process).
▶ Scalability and adaptability **▶ Modularity and "Plug&play declination"**	**3**	▶The number, depth and design of wells offer adaptability. The scalability should take into account the different components (carbon storage potential, geothermal potential) ▶ Each system depends on geological features and CCS/energy needs, and should thus be conceived specifically (no plug and play)	**3**	▶The number, depth and design of wells offer adaptability. The scalability should take into account the different components (carbon storage potential, geothermal potential) ▶ Each system depends on geological features and CCS/energy needs, and should thus be conceived specifically (no plug and play)	**2**	▶The number, depth and design of wells offer adaptability. However, considering implementation complexity and a high number of wells, the concept is only viable for very large-scale plants. ▶ The high level of expertise and lack of data for great depths prevent envisaging a plug&play system in the short term.	**3**	▶The number, depth and design of wells offer adaptability. Scalability should take into account the different components (carbon storage potential, geothermal potential) ▶ Each system depends on geological features and CCS/energy needs, and should thus be conceived specifically (no plug and play)
PERCEPTION BY STAKEHOLDERS	3		3		3		3	
▶ Legitimacy of the concept	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict.	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict.	3	▶ Socio-political perception of hybrid concepts is ill-known and difficult to predict.	3	▶ Socio-political perception of CCS is a challenge. Adjunction of the CCS component might be marginal for perception since the main system remains CCS.
READINESS	4		3		2		3	
▶ Proof of performance and of safety	**4**	▶Technico-economic feasibility has not been demonstrated. ▶ However, it relies on the assembly of different components that can be considered as mature.	**3**	▶Technico-economic feasibility has not been demonstrated. ▶ However, it relies on the assembly of different components that can be considered as mature.	**2**	▶The concept is a hybridization of hydrothermal geothermal exploitation, fossil/biomass power plant, energy storage and CCS. CCS and geothermal heat extraction have a relatively high TRL. However, the combination has not been demonstrated. Adjunction of the energy storage component and complexity of the holistic hybrid system raise a number of specific technical issues.	**3**	▶Technico-economic feasibility has not been demonstrated. ▶ However, it relies on the assembly of different components that can be considered as mature.
ENVIRONMENTAL RISKS & IMPACTS	**4,0**		**3,8**		**3,8**		**3,8**	
▶ Surface footprint	**5**	▶Surface occupation limited.	**5**	▶Surface occupation limited.	**5**	▶Surface occupation limited.	**5**	▶Surface occupation limited.
▶ Water consumption	**4**	▶Limited water consumption	**4**	▶Limited water consumption	**4**	▶Limited water consumption	**4**	▶Limited water consumption
▶ Guarantee of CO_2 containment and safety issues	**3**	▶ Containment of supercritical CO_2 requires: i. specific geological features (tight caprock), that need to be thorougly characterized; ii. rigorous monitoring and risk management.	**3**	▶ Containment of supercritical CO_2 requires: i. specific geological features (tight caprock), that need to be thorougly characterized; ii. rigorous monitoring and risk management.	**3**	▶ Containment of supercritical CO_2 requires: i. specific geological features (tight caprock), that need to be thorougly characterized; ii. rigorous monitoring and risk management.	**3**	▶ Containment of supercritical CO_2 requires: i. specific geological features (tight caprock), that need to be thorougly characterized; ii. rigorous monitoring and risk management.
▶ Seismic risk (whether natural or controlled)	**4**	▶ Seismic risk should be considered, as for any CCS or storage/exploitation involving large volumes, but is reduced by comparison with pure CCS since pressure increase is limited.	**3**	▶ Seismic risk should be considered, as for any CCS or storage/exploitation involving large volumes.	**3**	▶ Seismic risk should be considered, as for any CCS or storage/exploitation involving large volumes, but is reduced by comparison with pure CCS since it is limited with pressure management.	**3**	▶ Seismic risk should be considered as for any CCS or storage/exploitation involving large volumes.
TECHNICAL COMPLEXITY AND SCIENTIFIC CHALLENGES	**3,5**		**3,0**		**3,5**		**3,5**	
▶ Engineered technical complexity	**4**	▶ Drillings: separate drillings for CCS and for heat mining. ▶ No stimulation required ▶ Exploration phase and data can be mutualized, thus the technical complexity serves both systems. ▶ Handling water to avoid reinjection in the vicinity requires specific solutions.	**3**	▶ Drillings: mutualization of the number of wells with a well dedicated to both CO_2 injection and water reinjection. This limits the number of wells but increases technicity. ▶ No stimulation required ▶ Exploration phase and data can be mutualized, thus the technical complexity serves both systems.	**4**	▶ Drillings: drillings for CCS and for heat mining. Huff-puff wells. ▶ No stimulation required ▶ Exploration phase and data can be mutualized, thus the technical complexity serves both CCS and heat mining/thermal storage. ▶ Handling water and reinjection in a different reservoir raises specific challenges.	**4**	▶ Drillings: separate drillings for CCS and for heat mining. ▶ No stimulation required ▶ Both underground systems can be managed independantly. ▶ Surface imbrication involves some complexity.
▶ Degree of i) understanding of thermo-hydro-mechanical and microbio-geochemical phenomena and ii) management of the underground technical design	**3**	▶ Underground system modelling (THM) and managing (notably pressure management) with both systems involves some complexity. ▶ There is high temperature difference between the fluid produced and the reinjection temperature, which is a challenge for THM -CB modelling. ▶ The system involves several phases (water-phase, CO_2-phase).	**3**	▶ Underground system modelling (THM) and managing with both systems involves some complexity. ▶ A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling. ▶ The system involves several phases (water-phase, CO_2-phase).	**3**	▶ Underground system modelling (THM) and managing with both systems involves some complexity. ▶ The temperature of the underground thermal energy storage is high, which raises specific challenges. ▶ The system involves several phases (water-phase, CO_2-phase).	**3**	▶ Both underground systems can be managed independantly. ▶ A high temperature difference exists between the fluid produced and the reinjection temperature, which is a challenge for THM-CB modelling. ▶ The system involves several phases (water-phase, CO_2-phase).
CREDIBLE PATH TO COMMERCIALITY	**4,0**		**4,0**		**3,0**		**3,5**	
▶ Development risks	**4**	▶ Development risks are still high for CCS exploitation considering underground uncertainties and management of technical issues (injectivity, plume management, leakage risk, geochemistry, etc.). ▶ The synergetic use in the same reservoir allows mutualization of exploration and infrastructure and thus reduce development risks. ▶ The synergetic use in the same reservoir increases the operational risks dur to complexity increase. ▶ Pressure management limits pressure increase in the resevoir and thus limits leakage and seismic risks.	**4**	▶ Development risks are still high for CCS exploitation considering underground uncertainties and management of technical issues (injectivity, plume management, leakage risk, geochemistry, etc.). ▶ The synergetic use in the same reservoir increases operational risks due to complexity increase. The synergetic use in the same reservoir allows mutualization of exploration and infrastructure and thus reduces development risks.	**2**	▶ Development risks are still high for CCS exploitation considering underground uncertainties and management of technical issues (injectivity, plume management, leakage risk, geochemistry, etc.). ▶ Drilling depth is moderate but the number of wells is a challenge. The targeted temperature for underground storage is a challenge. ▶ The necessity of two aquifers with suitable characteristics increases the level of risk.	**4**	▶ Development risks are still high for CCS exploitation considering underground uncertainties and management of technical issues (injectivity, plume management, leakage risk, geochemistry, etc.). ▶ Considering the moderate temperature, the develoment risk for geothermal heat mining are limited.
▶ Investment costs **▶ Economic performance**	**4**	▶ Investment costs are high but mutualized (exploration phase and data are shared) ▶ No initialization phase ▶ The CCS and geothermal energy production performances in suitable contexts have already been demonstrated over years. Synergetic use in the same reservoir through pressure management has not been demonstrated yet. ▶ The business model benefits from a double source of revenue (energy and CCS)	**4**	▶ Investment costs are high but mutualized (the same drilling is used for CO_2 injection and water reinjection; exploration phase and data are shared) ▶ No initialization phase ▶ The CCS and geothermal energy production performances in suitable contexts have already been demonstrated over years. Synergetic use in the same reservoir and using a single well for both CO_2 injection and water reinjection has not been demonstrated yet. ▶ The business model benefits from a double source of revenue (energy and CCS)	**4**	▶ Investment costs are high. ▶ No initialization phase ▶ The CCS and geothermal energy production performances in suitable contexts have already been demonstrated over years. ▶ The business model benefits from a double source of revenue (energy and CCS)	**3**	▶ Investment costs are high. ▶ No initialization phase ▶ The CCS and geothermal energy production performances in suitable contexts have already been demonstrated over years. ▶ The business model relies on CCS revenues only.

Appendix 8.2 - Infographics

8.2.1 Literature review on concepts and projects combining geothermal energy use and CCS

WP1

LITERATURE REVIEW ON CONCEPTS AND PROJECTS COMBINING GEOTHERMAL ENERGY USE AND CCS

Annick Loschetter, Christophe Kervévan, Rowena Stead

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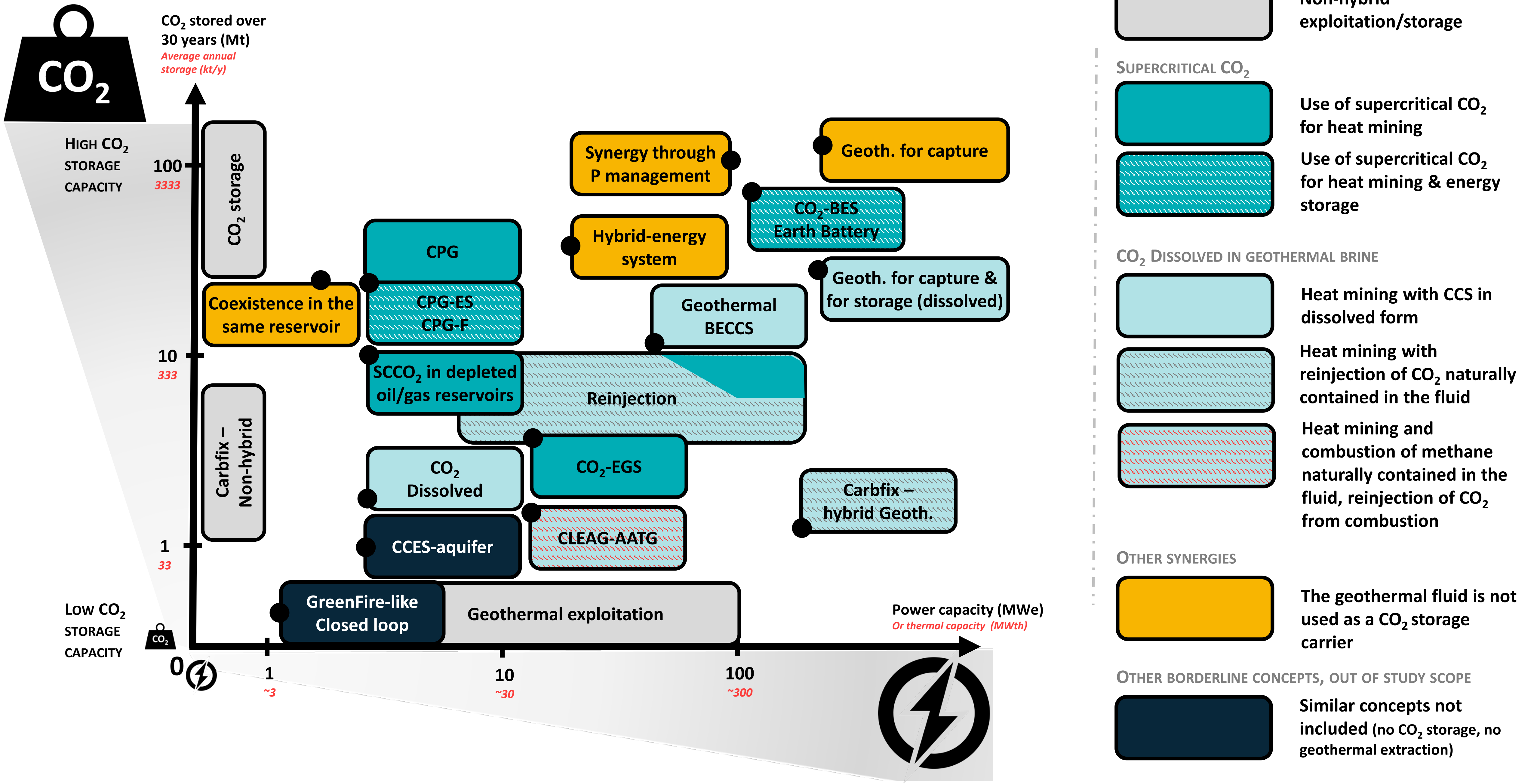
AN OVERVIEW



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
CO_2 Dissolved
CCES-aquifer
GreenFire-like Closed loop
Geothermal exploitation
Synergy through P management
Hybrid-energy system
Reinjection
CO_2-EGS
CLEAG-AATG
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)

LEGEND

- Depth
- Temperature
- Mainly mineral trapping (rapid CO_2 mineralization)
- Mainly solubility trapping (CO_2 dissolved in brine)
- Mainly structural trapping (e.g. below a tight caprock)

- Geothermal power plant (heat &/or electricity)
- External CO_2 emitter
- Hybrid power plant (geothermal & other)
- Water tank
- Gas engine (heat &/or electricity)

- Mainly water Or brine
- Mainly CO_2

- Brine
- Supercritical CO_2
- Brine with dissolved CO_2
- Liquid CO_2
- Water steam with gas CO_2
- CO_2 (e.g. gas phase)

TECHNICO-ECONOMIC COMPLEXITY

When data are non-comparable or unavailable, we rely on qualitative assessment

- Well drilling (high number, great depth vs. more simple layout)
- Stimulation required
- System initialization required
- Geochemical management (complex issues vs. accessible issues)
- Complex system (either underground or surface installations)
- Free phase of buoyant CO_2, thus requiring efficient containment
- Seismicity issue
- Integration in electricity network for storage
- Water not entirely reinjected (should be managed)
- Use/share of existing infrastructure

DEFINITION OF THE INDEXES OF SERVICES RATIO

Foreword: *The proposed index has been designed for the present study only. It aims to convey an order of magnitude and allow comparison between concepts. It should not be taken out of context or be considered a rigorous economic indicator.*

CO_2	**1 MtCO_2 stored over 30 years**	→	**30 M$** [Moderate CO_2 price from IEA: 30 $/t$CO_2$]
	Electricity production with power capacity 1 MWe	→	**30 M$** [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.

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Summary sheets – Hybrid concepts

2.1 Overview of pilots

1 Use of supercritical CO_2 as a heat vector for geothermal exploitation and/or Energy storage

2.2 Water-driven geothermal heat extraction with CO_2 injection to achieve near-zero CO_2 geothermal production

2.3 Water-driven geothermal heat extraction with injection of CO_2 in dissolved form for CCS

3 Other synergies (geothermal fluid and CO_2 for CCS are handled separately)

4 Other borderline concepts (out of study scope)

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CPG – CO_2 Plume Geothermal

1 - 4 km

80 to 200°C

External input 5-30 kg/s

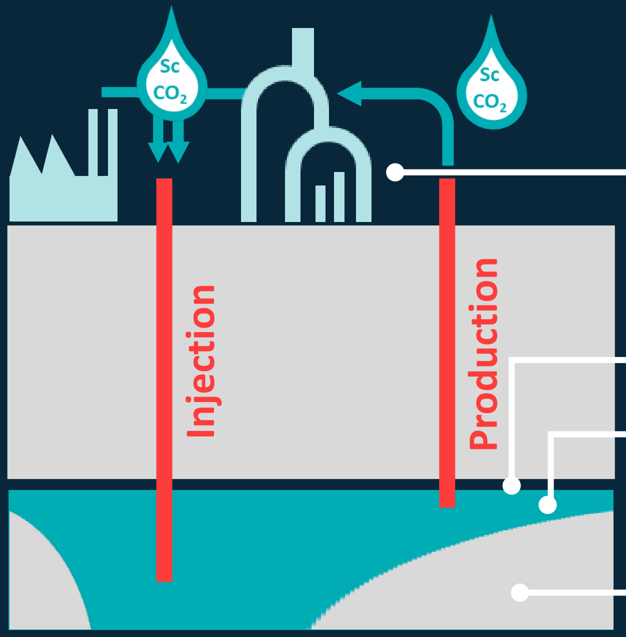
Supercritical CO2 100-300 kg/s

5-10% loss

+ Outstanding performance by combining non-intermittent renewable energy production and CO2 storage from an external emitter
Wide potential of replicability
Efficiency higher with Sc-CO_2 than with water

– High investment cost
Needs Initialization (months or year(s))
Tricky design for long-term exploitation
CO_2 containment and leakage risk issue

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



Geothermal power plant with CO_2-compatible turbine or ORC turbine

Containment (e.g. caprock)

Supercritical CO_2 Structural trapping

Sedimentary porous and permeable hydrothermal reservoir

CPG consists in using supercritical CO_2 ($ScCO_2$) instead of brine as a heat vector in hydrothermal reservoirs (porous and permeable sedimentary formations) 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 reaches the production well.
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% - +200% 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 the CO_2 remains contained at depth, it leads to significant amounts of CO_2 stored after 30 years of operation.

Services provided

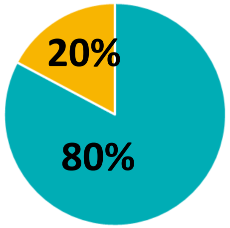
▶ Energy production

1 – 6 MWe

▶ CO2 storage

5 – 30 Mt CO_2 over 30 years

▶ Energy Storage Service



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

Implementation complexity

2-5 wells

Initialization (months or year(s))

Containment Sc CO_2

CO_2-EGS – Enhanced Geothermal System

3 - 6 km

160 to 300°C

External input 5-15 kg/s

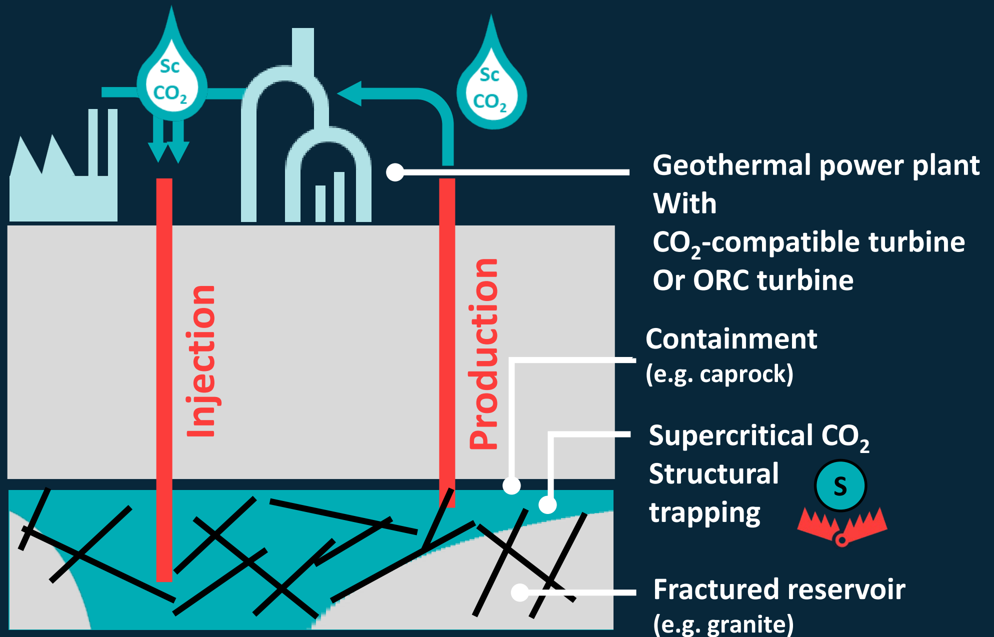
Supercritical CO_2 100-300 kg/s

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

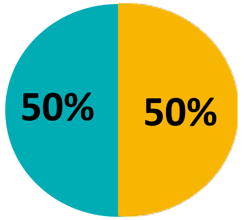
TRL First paper in 2000 (Brown)
Tens of modelling papers by different teams (mainly: case studies, underground modelling, geochemical modelling, system modelling)
Cradle: US



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
- **CO2 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

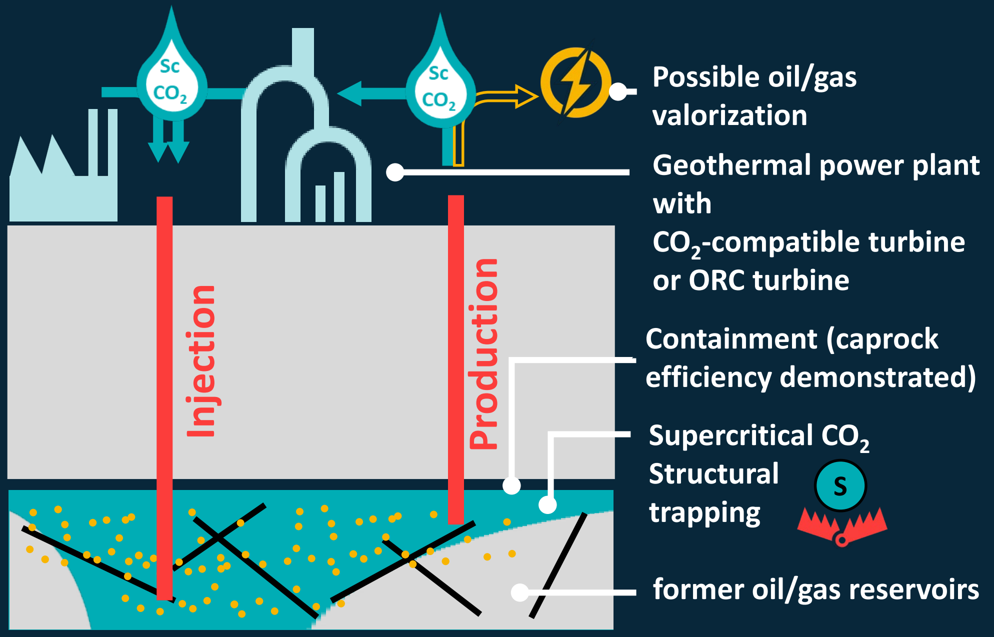
Supercritical CO_2
20-100 kg/s

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



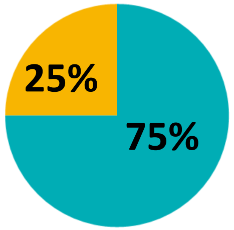
CO_2 has been widely used to assist/enhance production in CO_2 enhanced oil recovery (CO_2-EOR) and CO_2 enhanced gas recovery (CO_2-EGR). The addition of CO_2 increases the overall pressure of an oil/gas reservoir, and thus increases production.

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

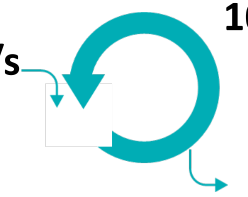
CPG – ES (Energy Storage) or F (Flexible)

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

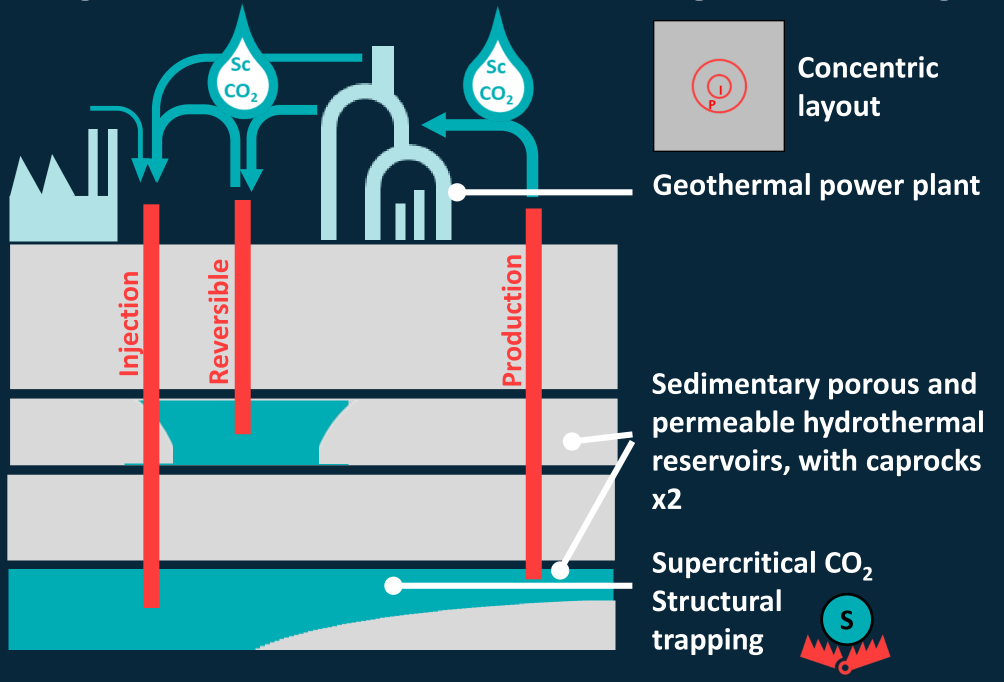


5% loss

+
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

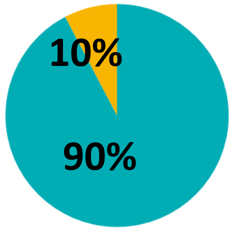
TRL
First paper in 2014
A few scientific articles.
Cradle: US



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.

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)

Implementation complexity

> 6 wells
Horizontal
2 aquifers

Initialization
(2 years)

Complex hybrid plant

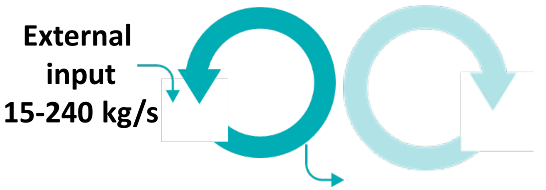
Integration in electricity network

Containment Sc CO_2

Earth Battery - BES (Bulk Energy Storage)

3-5 km

130 - 200°C

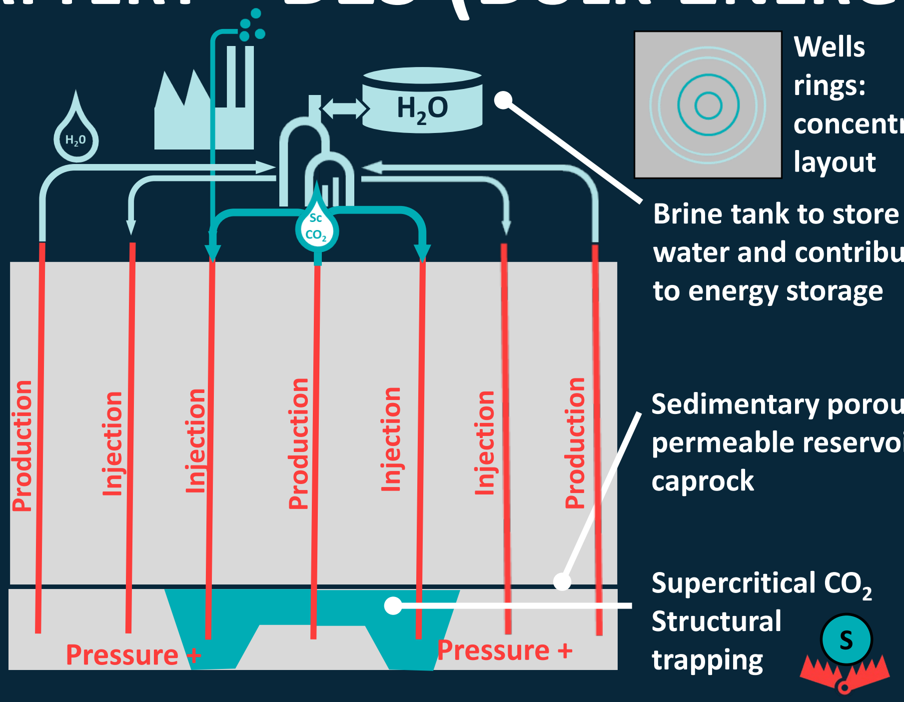


Multi-services: CO_2 storage, base-load electricity production, electricity storage.
Outstanding performance
High flexibility between services
Pressure management limits leakage risks and increases efficiency

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

TRL

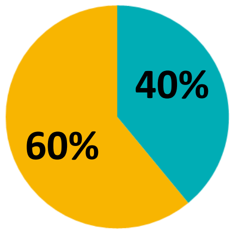
First paper in 2016
A few scientific articles.
Cradle: US



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 (H_2O)

Complex system

Integration in electricity network

Containment Sc CO_2

SUMMARY SHEETS – HYBRID CONCEPTS

2.1 OVERVIEW OF PILOTS

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

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

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

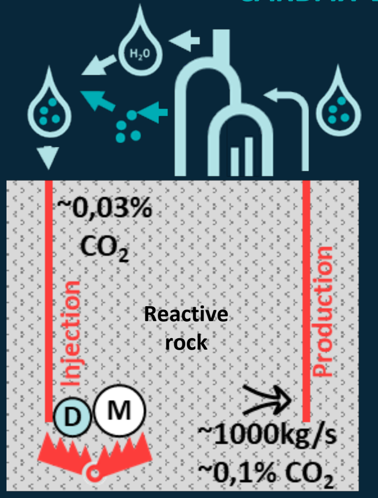
3 OTHER SYNERGIES (THE GEOTHERMAL FLUID AND THE CO_2 FOR CCS ARE HANDLED SEPARATELY)

4 OTHER BORDERLINE CONCEPTS (OUT OF STUDY SCOPE)

Portfolio of demo sites for neighbouring concepts

Hellisheidi and Nesjavellir (Iceland)

Carbfix-like concept

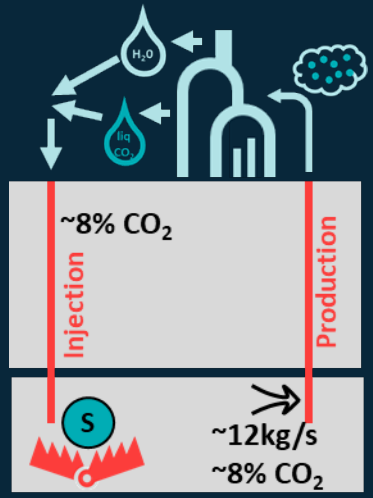


0.7-2 km | 200-300 °C
200-400 MWe | 10-40 kt/y

- Carbfix initial concept
- Projects: GECO, SUCCEED
- Pilot since 2011, Demo sites since 2014
- 33% of CO_2 reinjected

Castelnuovo (Italy)

Total CO2-reinjection concept

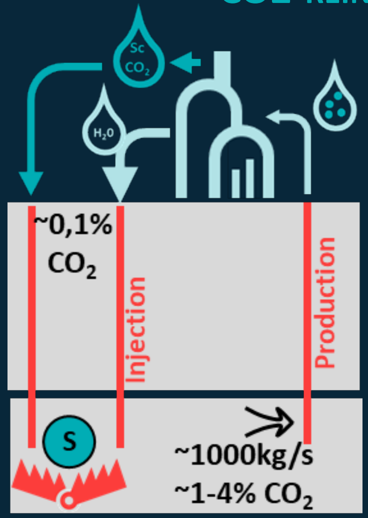


3.5 km | 280°C
~ 5 MWe | ~30 kt/y

- First project with total reinjection objective
- Project: GECO
- Demonstrator in stand-by
- 100% of CO_2 reinjected

Kizildere (Turkey)

CO2-reinjection concept

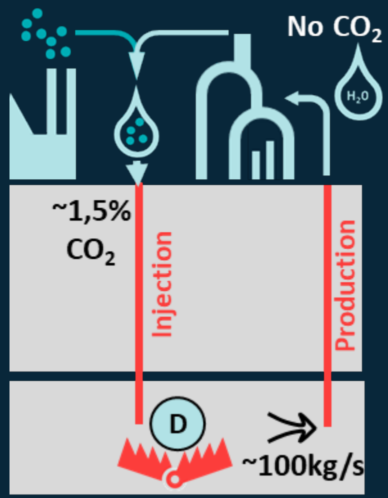


1.5 km | 200°C
~200 MWe | ~30 kt/y

- Supercritical CO_2 reinjected
- Projects: GECO, SUCCEED
- Demonstrator currently deployed
- ~5% of CO_2 reinjected

Paris basin (France) (& Bochum Germany?)

CO2-Dissolved-like concept

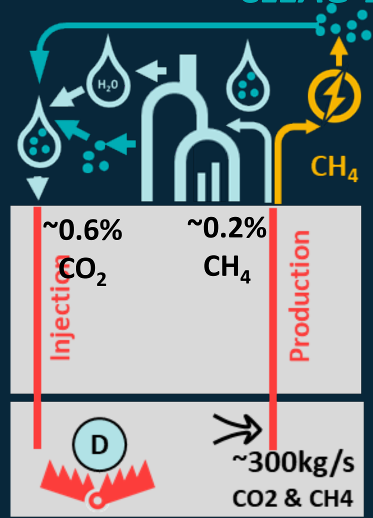


1.7 km | 60-80 °C
4-6 MWth | ~45 kt/y

- Project: CO2-Dissolved &Co
- Pilot in preparation
- CO_2 from external emitter

Croatia

CLEAG-like concept



2 km | 100-120 °C
~15MWe 80MWth | ~56 t/y

- CLEAG –AATG
- NER 300
- Pilot, production since 2017
- 100% of CO_2 reinjected

Depth | T° | Electricity (and heat) production | Heat production only | Annual CO_2 storage

Brine with dissolved CO_2 | Brine | Liquid CO_2 | Supercritical CO_2 | CO_2 (e.g. gas phase) | Water steam with gas CO2

M Mainly mineral trapping | D Mainly solubility trapping | S Mainly structural trapping

Geothermal power plant (heat &/or electricity) | Gas engine (heat &/or electricity) | External CO_2 emitter

Categorization of Water-driven geothermal heat extraction with CO_2 (re)injection

	Geothermal fluid characteristics	CO_2 origin	Injection form	Trapping mechanism in the middle term	Philosophy
"CO_2-Dissolved-like" concept	**low natural dissolved CO_2 content**	**External origin**	Dissolved	Mainly solubility	**Dual objective**
CO_2-reinjection concept	**Significant content of CO_2 and other NCG**	Geothermal fluid	Dissolved	Mainly solubility	**Towards zero-emission geothermal power plant**
			Liquid or Supercritical	Mainly structural	
"Carbfix-like" concept	**Might contain NCG/CO_2**	Generally geothermal-fluid (or external origin)	Dissolved	**Mainly mineral**	**CCS-driven concept at origin, dual objective then.**
"AATG-CLEAG-like" concept	**Significant content of methane (and possibly NCG)**	Geothermal fluid and methane combustion	Dissolved	Mainly solubility	**Towards zero-emission geothermal power plant**

Summary sheets – Hybrid concepts

2.1 Overview of pilots

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2.2 Water-driven geothermal heat extraction with CO_2 injection to achieve <u>near-zero CO_2 geothermal production</u>

2.3 Water-driven geothermal heat extraction with injection of CO_2 in dissolved form <u>for CCS</u>

3 Other synergies (the geothermal fluid and the CO_2 for CCS are handled separately)

4 Other borderline concepts (out of study scope)

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

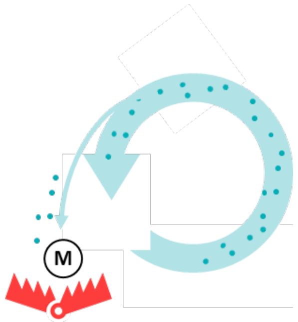
Geoscience for a sustainable Earth
brgm

ieaghg

CarbFix-like concept

0.7-2 km

200 to 300°C



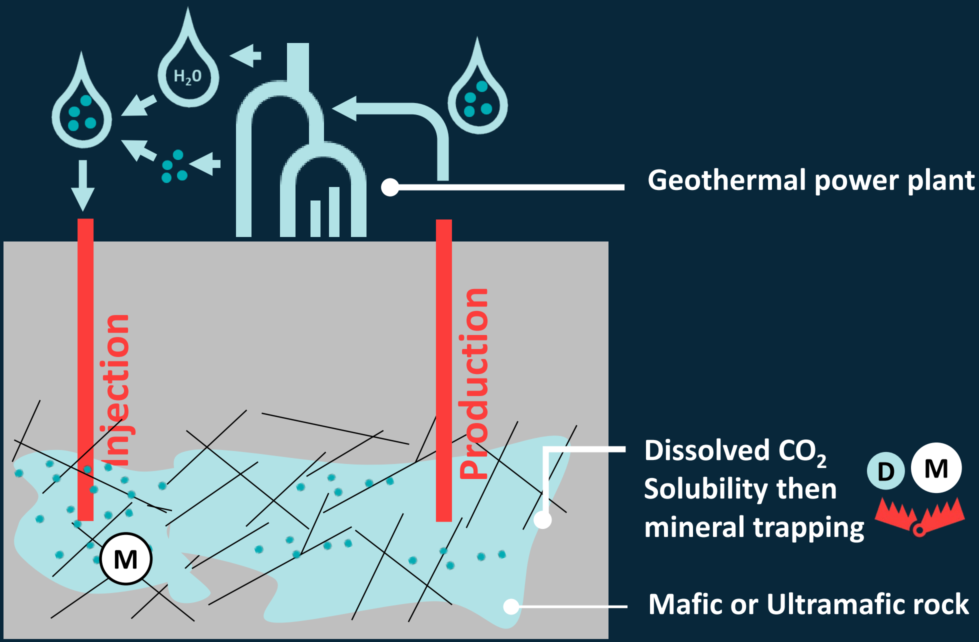
Water ~1000 kg/s with CO_2: 0.1% by mass (1kg/s)

→ 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.

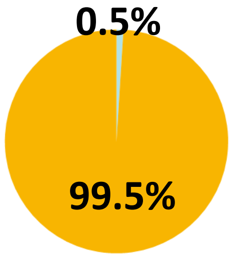
TRL
Pilot since 2011, demonstrator since 2014
Tens of papers, 2 on-going multi-partners projects in Europe.
Cradle: Iceland
Recent new project in New Zealand



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

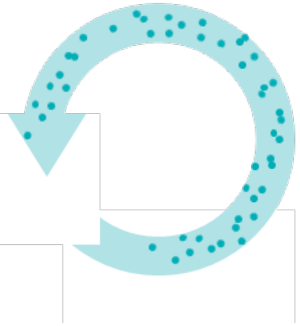
Geochemical management

Seismicity issue

CO_2-REINJECTION CONCEPT – DISSOLVED OR SUPERCRITICAL

1.5-3.5 km

150 to 300°C



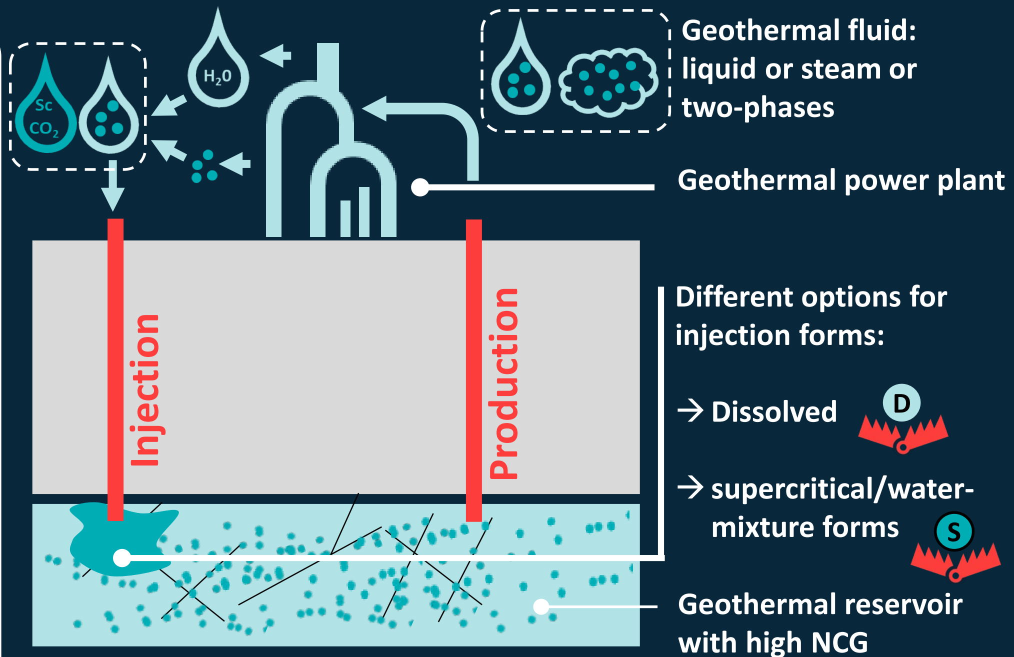
Water ~10-1000 kg/s with CO_2: 1-8% by mass

→ 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

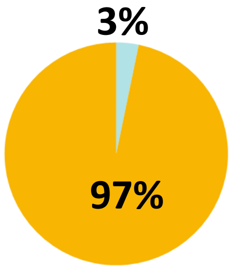
- **Energy production**

  5 - 300 MWe

- **CO_2 Avoided**

  0.3 -18 Mt CO_2 over 30 years

- **Energy Storage Service**



Index of services ratio
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IMPLEMENTATION COMPLEXITY

Variable number of wells

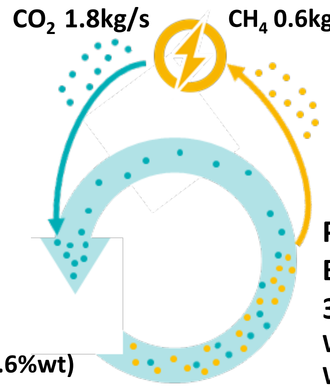
Geochemical management

Containment CO_2

CLEAG/AATG-LIKE CONCEPT

2 km

100 to 120°C



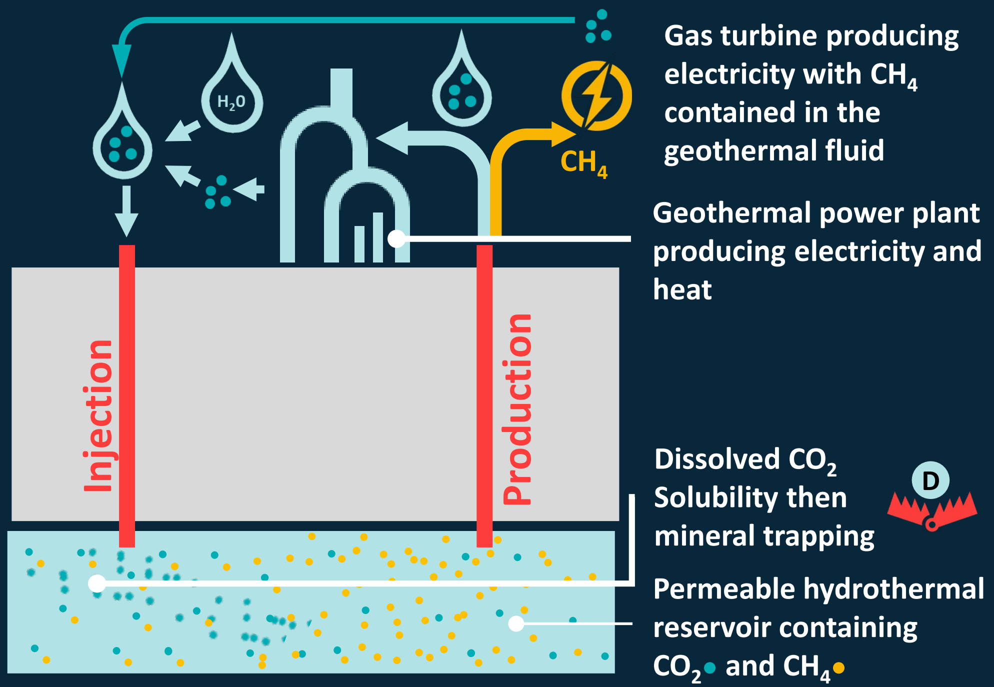
Injected:
Brine
320 kg/s
With CO_2 (0.6%wt)

Produced:
Brine
320 kg/s
With CH_4 (0.2%wt)
With CO_2 (0.006%wt)

+
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



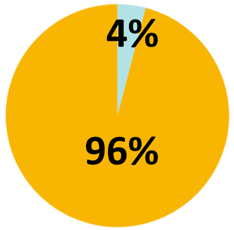
The concept consists in fully utilizing the energy potential of hot brines. It targets geothermal fluids that contain gases, between others combustible gases. In contrast to conventional geothermal power plants, CLEAG's hybrid system uses two sources for its energy production:

- 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

Summary sheets – Hybrid concepts

2.1 Overview of pilots

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2.3 Water-driven geothermal heat extraction with injection of CO_2 in dissolved form for CCS

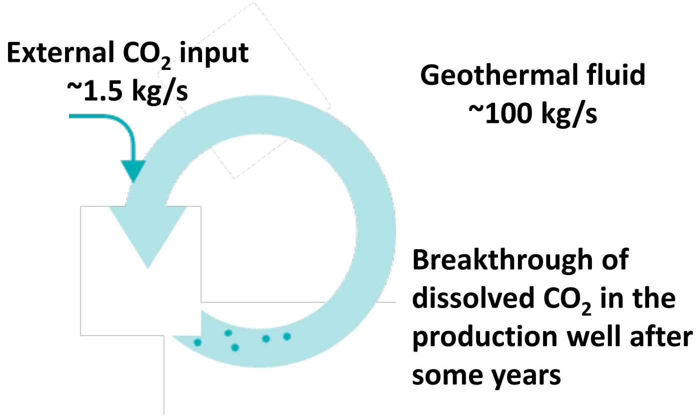
3 Other synergies (the geothermal fluid and the CO_2 for CCS are handled separately)

4 Other borderline concepts (out of study scope)

CO2-DISSOLVED-LIKE CONCEPT

1.7 km

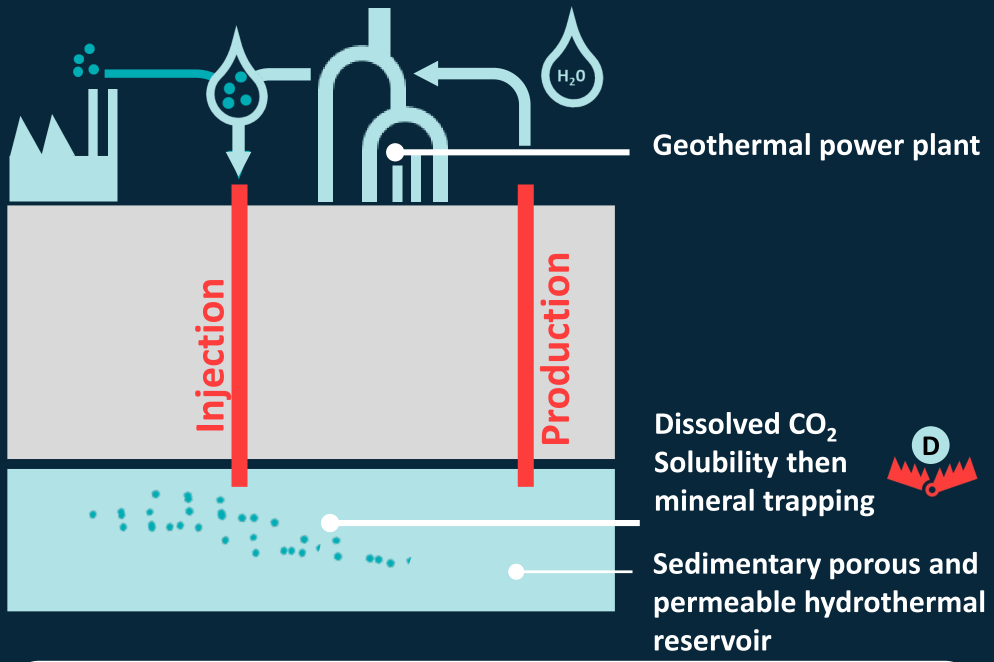
60 to 80°C



+
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

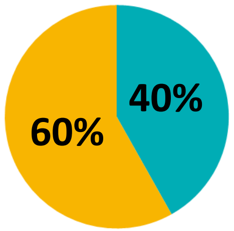
TRL
First published in 2014
Several scientific articles
Pilot in planning in France
Cradle: France



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

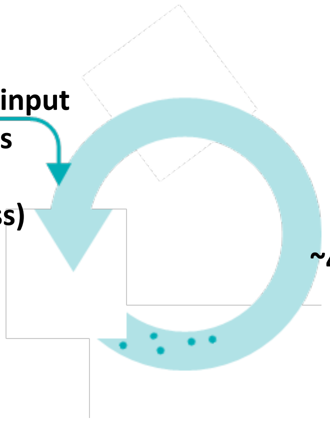
Doublet

Geochemical management

GEOTHERMAL BECCS (BIOENERGY – CCS)

0.5-3 km

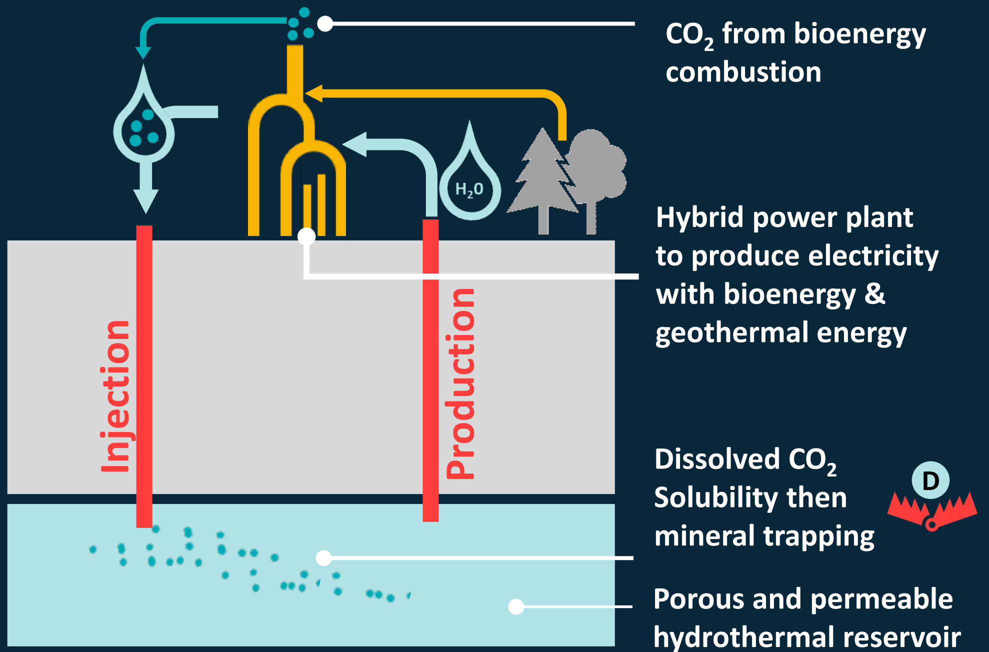
160°C



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

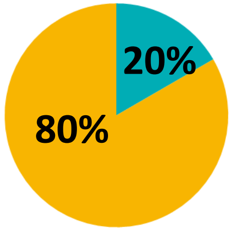
TRL
First published in 2022
1 article
Cradle: New Zealand



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
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IMPLEMENTATION COMPLEXITY

At least a doublet

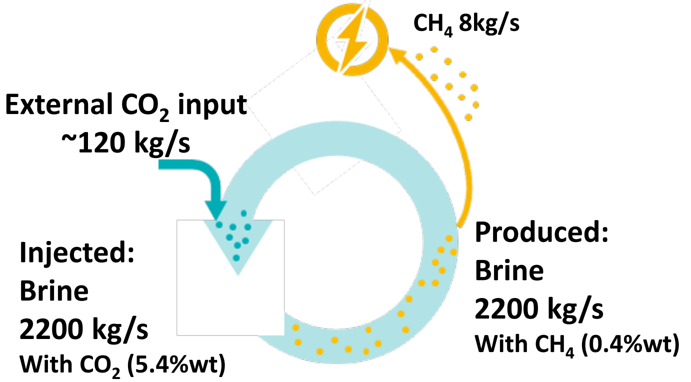
Geochemical management

Complex hybrid plant

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

3 km

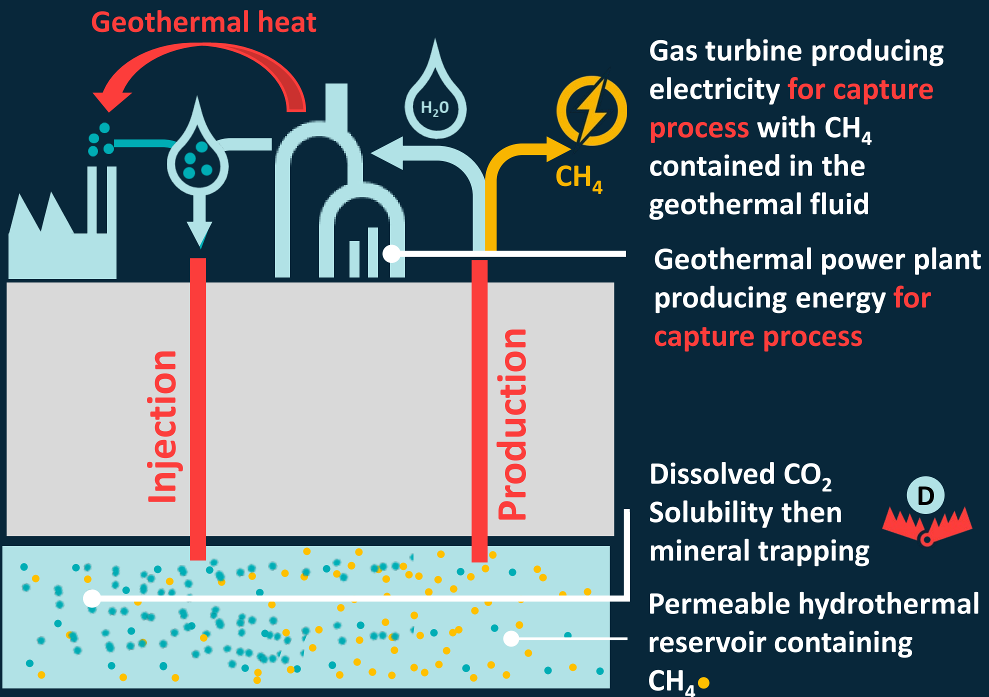
150°C



+
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:

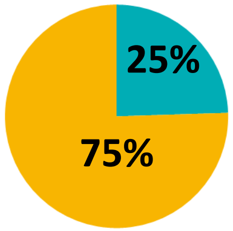
- Hot geothermal fluid (100-120°C) (~250MWe)
- Combustible gases dissolved in the geothermal fluid to produce electricity (~500 MWth)

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
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IMPLEMENTATION COMPLEXITY

Tens of wells

Geochemical management

Summary sheets – Hybrid concepts

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3 Other synergies (the geothermal fluid and the CO_2 for CCS are handled separately)

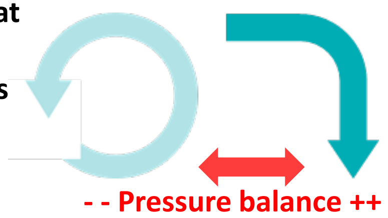
4 Other borderline concepts (out of study scope)

Synergy through pressure management

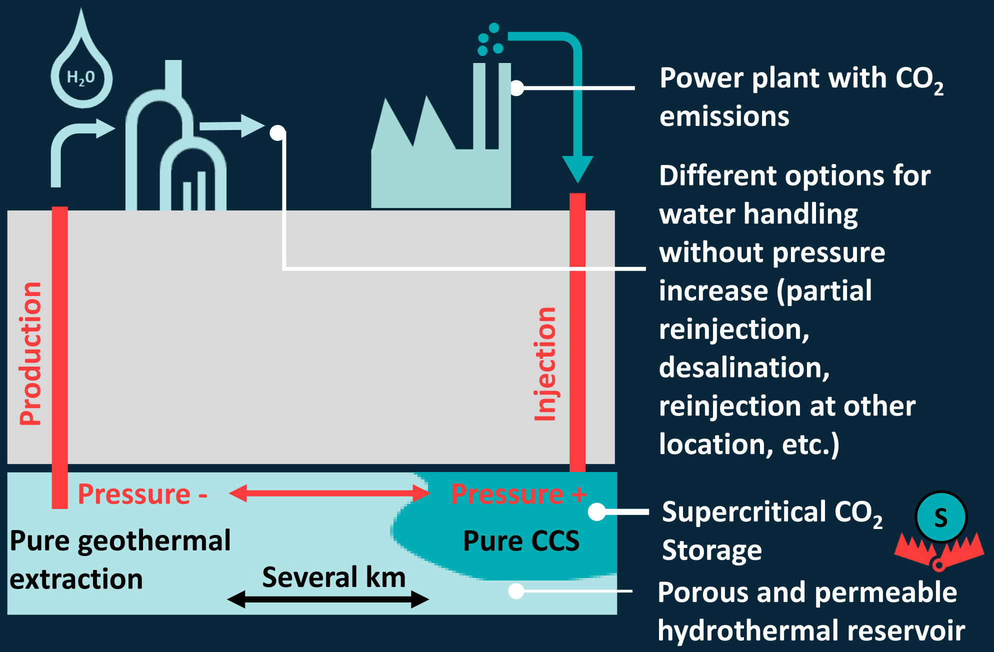
1-3 km

150°C

Brine for heat extraction ~50-250 kg/s



CO_2 ~100-500 kg/s for CCS



Services provided

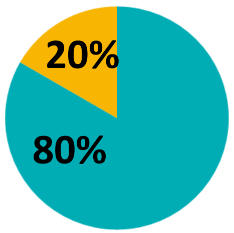
▶ **Energy production**

~50-500 MWth

▶ **CO_2 storage**

~100-500 Mt CO_2 over 30 years

▶ Energy Storage Service



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

+

Outstanding performance by combining non-intermittent renewable energy production and CO_2 storage from an external emitter
High CO_2 storage quantities
Sharing of data limits costs
Seismic risks reduced through pressure management

−

Underground system modelling and management with both systems involves some complexity
CO_2 containment and risk/impact issues

TRL

Published in 2011
A few articles
Cradle: US, Norway, Denmark

For CCS, CO_2 injection provokes a pressure increase in the reservoir. It limits injectivity and storage capacity, and increases seismic and leakage risks. Therefore, solutions of Active CO_2 Reservoir Management (ACRM) have been proposed by different authors to improve CCS performance. They consist in 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 CO_2 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 improves CO_2 storage capacity.

Implementation complexity

~2-10 wells

Complex reservoir management and modelling

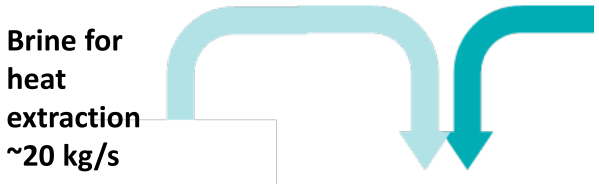
Water handling

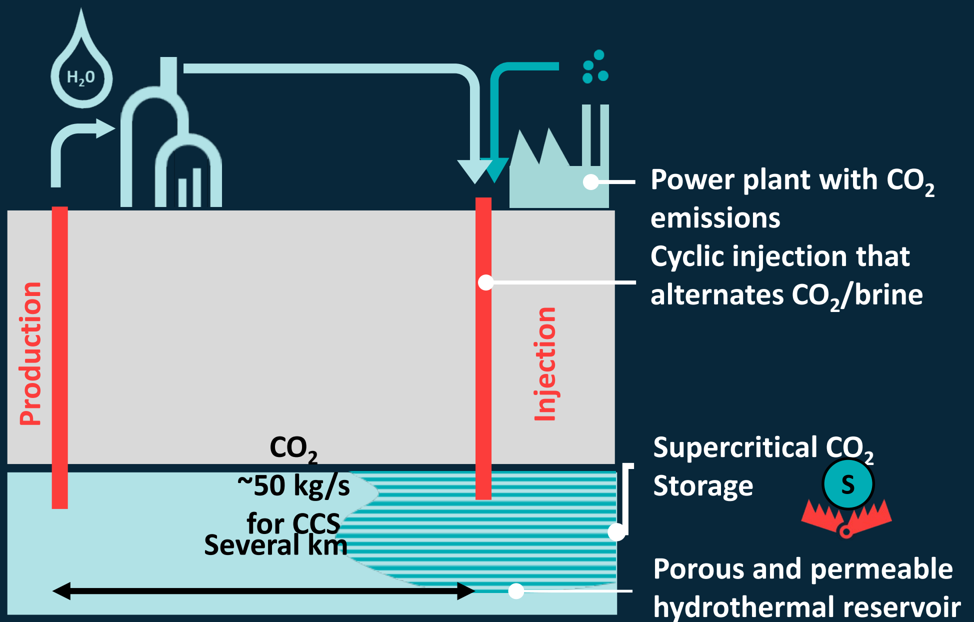
Containment CO_2

Synergetic dual use in the same reservoir

~1 km

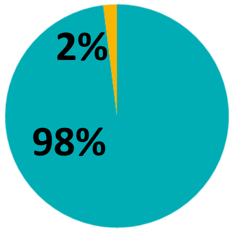
~50°C





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 economic assumptions within the study)

+

Outstanding performance by combining non-intermittent renewable energy production and CO_2 storage from an external emitter
High CO_2 storage quantities
Sharing of data and of injection well limits costs

−

Underground system modelling and managment with both systems involves some complexity
CO_2 containment and risk/impact issues

TRL

Published in 2013
1 article
Cradle: Germany

The same reservoir is used for both CCS and geothermal heat mining. It allows synergies for the exploration phase, data acquisition, and for some infrastructure.

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 CO_2 injection and brine reinjection.

Their results demonstrate that the competitive character between the technologies can be overcome and that synergetic reservoir utilization is possible in the chosen study area.

Implementation complexity

~2 wells

Complex reservoir management and modelling, injection cycles

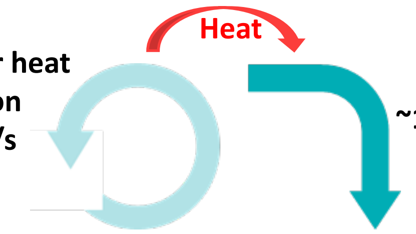
Containment CO_2

Sc CO_2

Hybrid Energy System

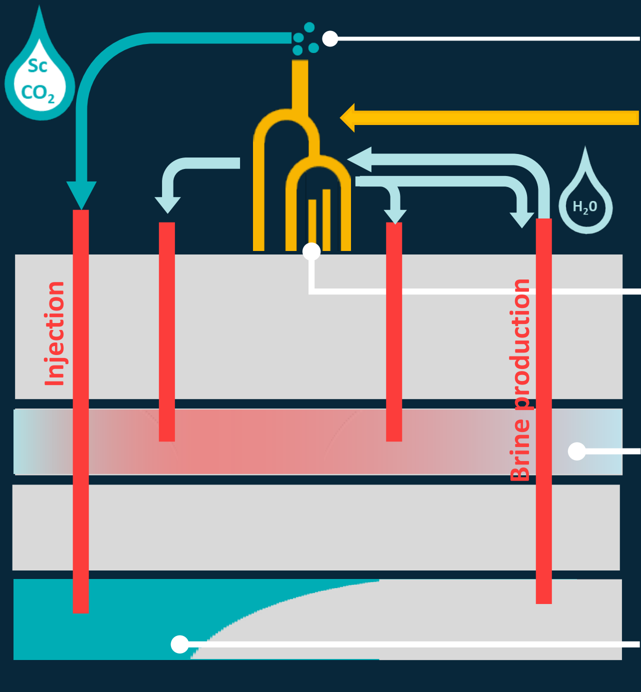
1-2 km

90-200°C



Brine for heat extraction ~300 kg/s

CO_2 ~100 kg/s for CCS



CO_2 from combustion

Fossil/biomass energy

Hybrid power plant to produce electricity with fossil/biomass energy & geothermal energy

AquiferThermal Energy Storage

Supercritical CO_2 Storage

+ 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

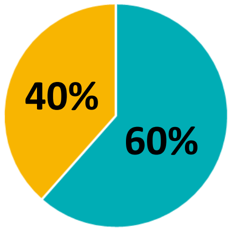
– Requires two suitable reservoirs for both uses
High investment costs (two independent systems with limited synergy)
High complexity and large-scale

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

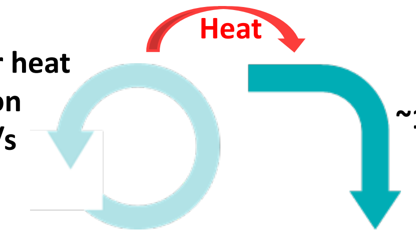
? Water not entirely reinjected (should be managed)

Containment CO_2

CCS WITH GEOTHERMAL ENERGY FOR CAPTURE PROCESS

1.5-2 km

150°C



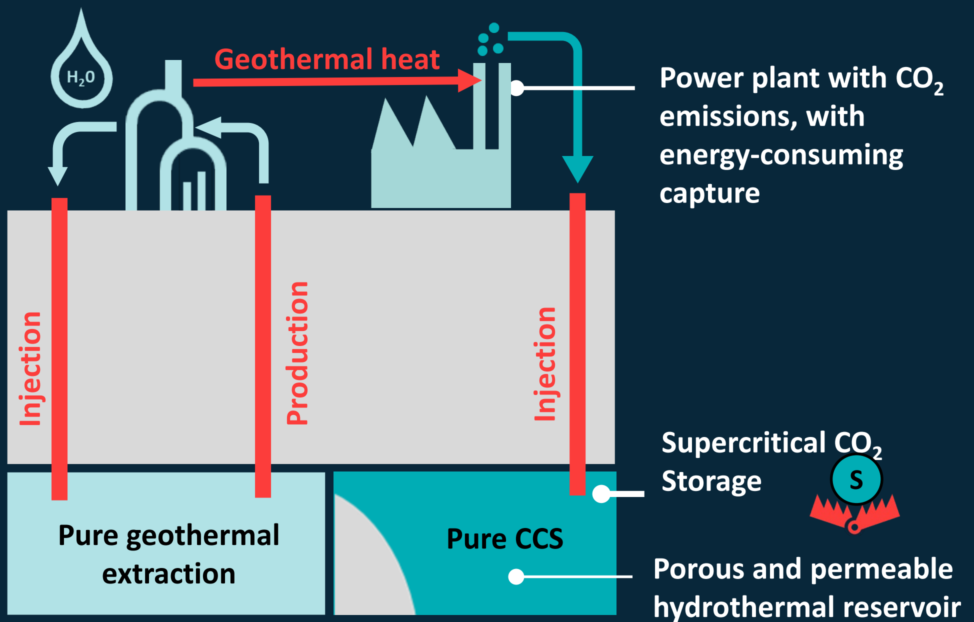
Brine for heat extraction ~300 kg/s

CO_2 ~150 kg/s for CCS

+ Improvement of CCS environmental benefits
  High CO_2 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 containment and risk/impact issues

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



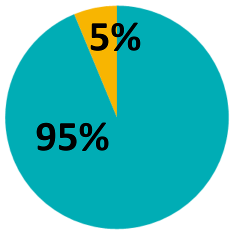
The main objective remains the storage of CO_2. When analyzing the whole chain, the authors pointed out that the energy consumed for the process of CO_2 capture represents a non-negligible penalty for carbon reduction. In order to improve the benefit of CO_2 storage, the authors investigated the potential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

With equivalent coal consumption, using geothermal energy allows a saving of 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 by 10M We 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 economic assumptions within the study)

IMPLEMENTATION COMPLEXITY

~5 wells

Complexity (2 reservoirs with service articulation)

Containment CO_2

Summary sheets – Hybrid concepts

2.1 Overview of pilots

1 Use of supercritical CO_2 as a heat vector for geothermal exploitation and/or energy storage

2.2 Water-driven geothermal heat extraction with CO_2 injection to achieve <u>near-zero CO_2 geothermal production</u>

2.3 Water-driven geothermal heat extraction with injection of CO_2 in dissolved form <u>for CCS</u>

3 Other synergies (the geothermal fluid and the CO_2 for CCS are handled separately)

4 Other borderline concepts (out of study scope)

- **CCES** (Compressed CO_2 Energy Storage)
- **CAES** (Compressed Air Energy Storage) with CO_2 as a cushion gas
- *Not included because no geothermal heat mining; pressure is exploited, not thermal properties*

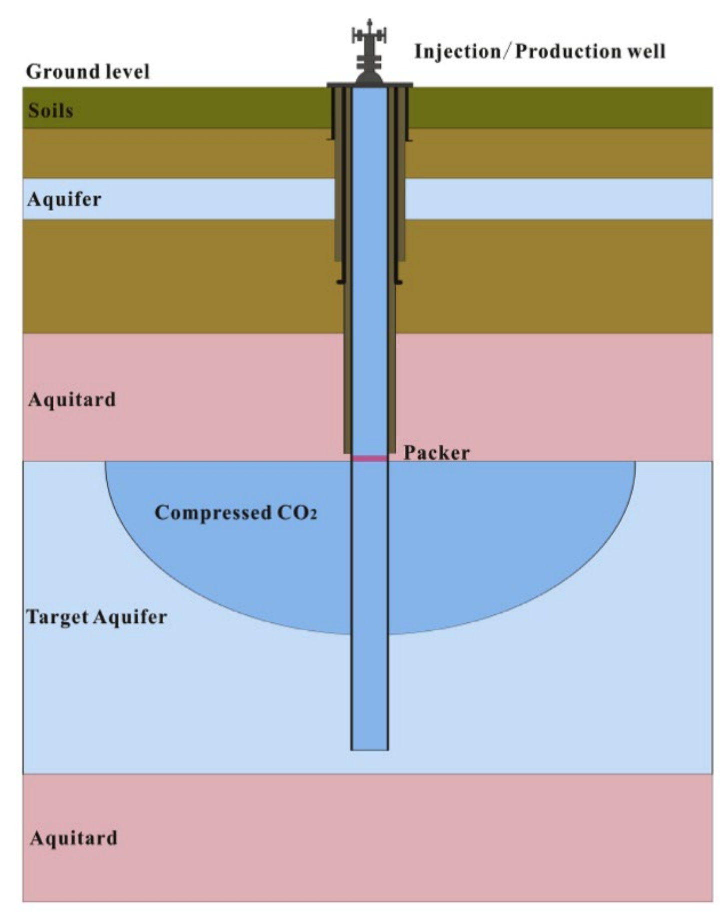


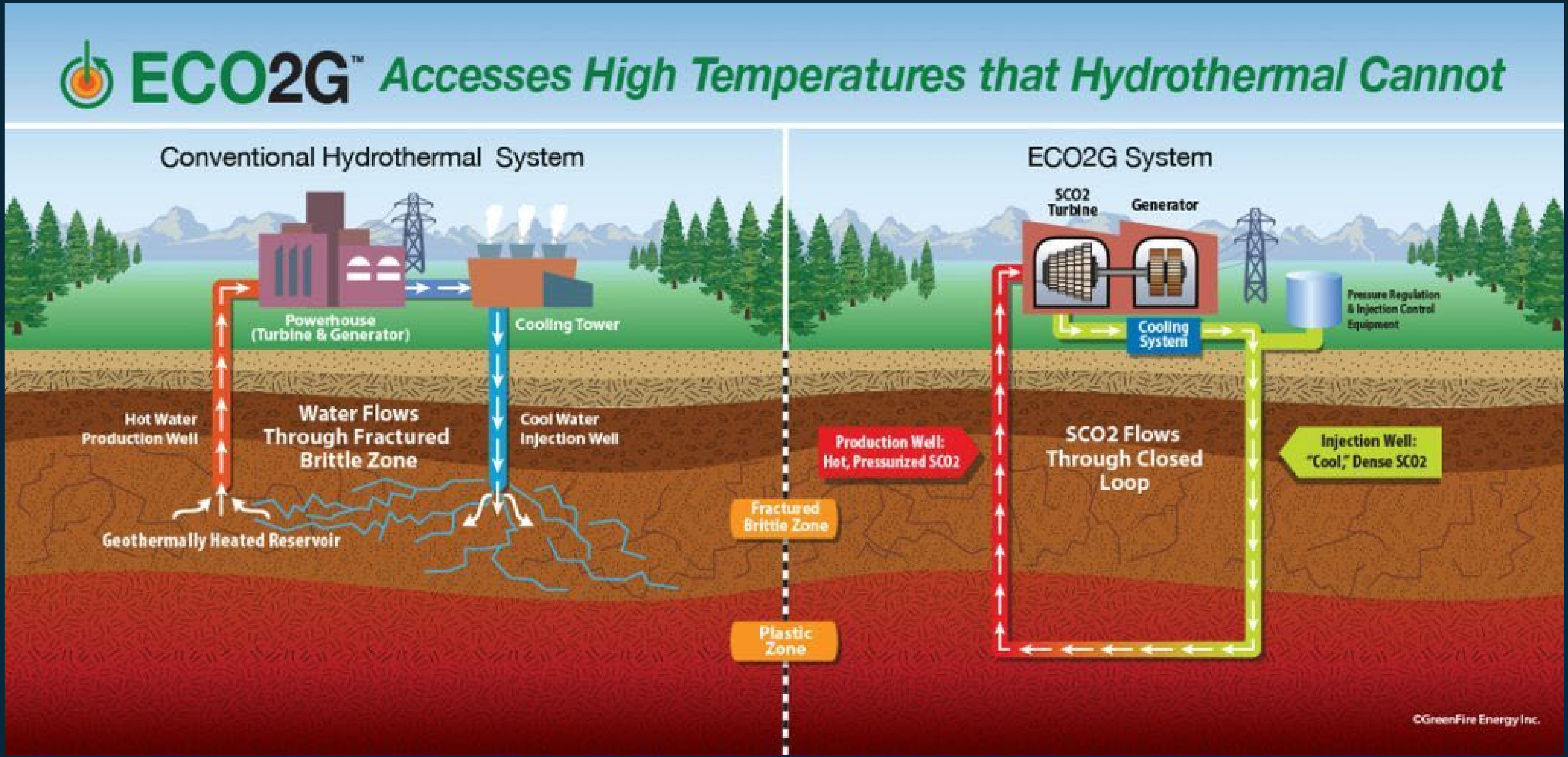
Table I. Characters of different kinds of CAES, ETES (TEES), and CCES systems.

System	Round trip efficiency (%)	Energy density (kWh/m^3)	Main drawbacks
Conventional CAES	42, 54 (with recuperator) [6]	2–6 [17]	Fuel combustion and large storage volume in fixed and rigid reservoir
Adiabatic CAES	Around 70 [18]	Similar to conventional CAES [17]	Low energy density
Isobaric CAES with PHS [12]	Higher in CAES part but lower in hydraulic part	Higher than conventional CAES	Dependence on geographical conditions
Underwater CAES [13]	Up to 71	Higher than conventional CAES	Dependence on geographical conditions
Liquid air energy storage [14]	Below 50	Higher than conventional CAES	Low cycle efficiency
Supercritical CAES [15]	67.41	96	High cost of extremely low temperature for liquid air storage
Compressed air storage with humidification [16]	Above 60	Similar to conventional CAES	Much water consumption and low energy density
ETES/TEES	Up to 64 [19]	About 10 [20]	Complicated operations of multi-tank heat storage and ice generation
Isothermal TEES [20]	Around 70	14–15	Complicated machinery and operation
Liquid CCES [21]	56.64	36.12	Limited round trip efficiency
Transcritical CCES [22]	60.69	8.07	Complicated thermal storage technique
CCES with saline aquifer storage [23]	63.35 for transcritical operation and 62.28 for supercritical operation	497.68 for transcritical operation and 255.20 for supercritical operation	Dependence on the geographical conditions and use of fossil fuel

CAES, compressed air energy storage; ETES, electrothermal energy storage; TEES, thermo-electrical energy storage; CCES, compressed CO_2 energy storage.

►Closed-loop systems with CO_2 as a fluid vector

- *Not included because no CCS*



8.2.2 Comparison between concepts

WP2
COMPARISON BETWEEN CONCEPTS & INFOGRAPHICS

Annick Loschetter, Thomas Le Guénan, Christophe Kervévan, Rowena Stead

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Égalité
Fraternité

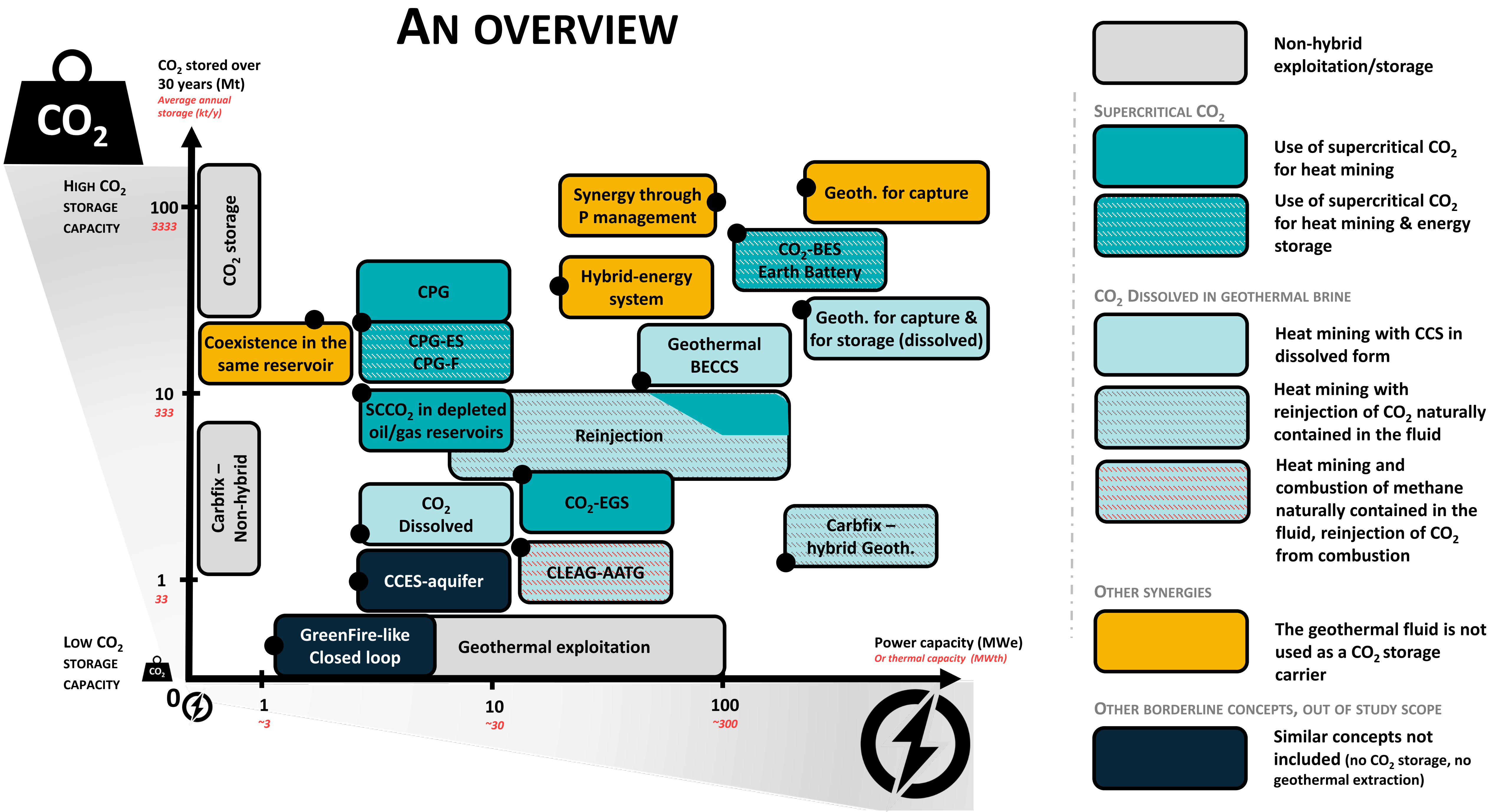
Geoscience for a sustainable Earth
brgm

ieaghg

WP2

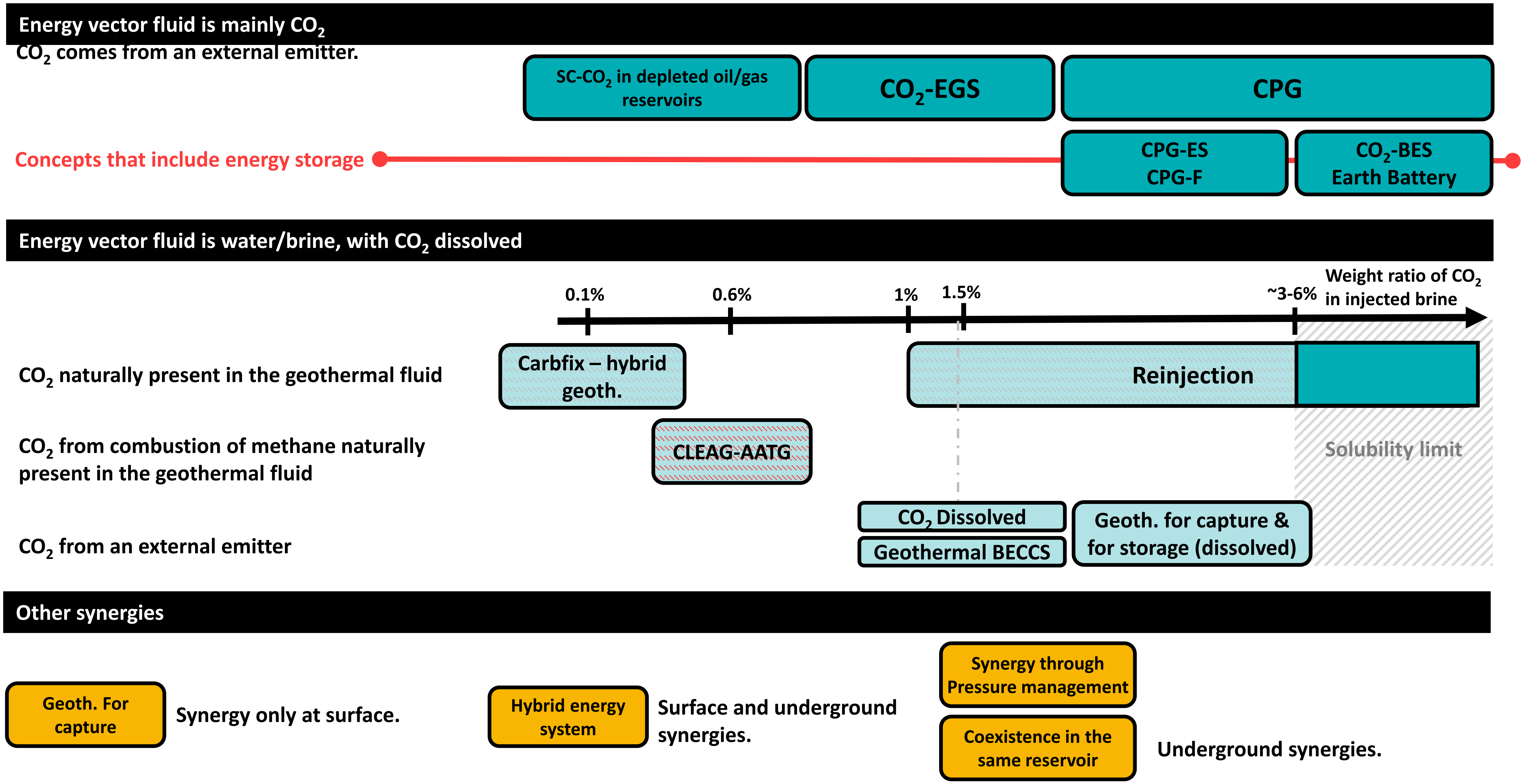
INFOGRAPHICS

COMPARISON OF CRITERIA

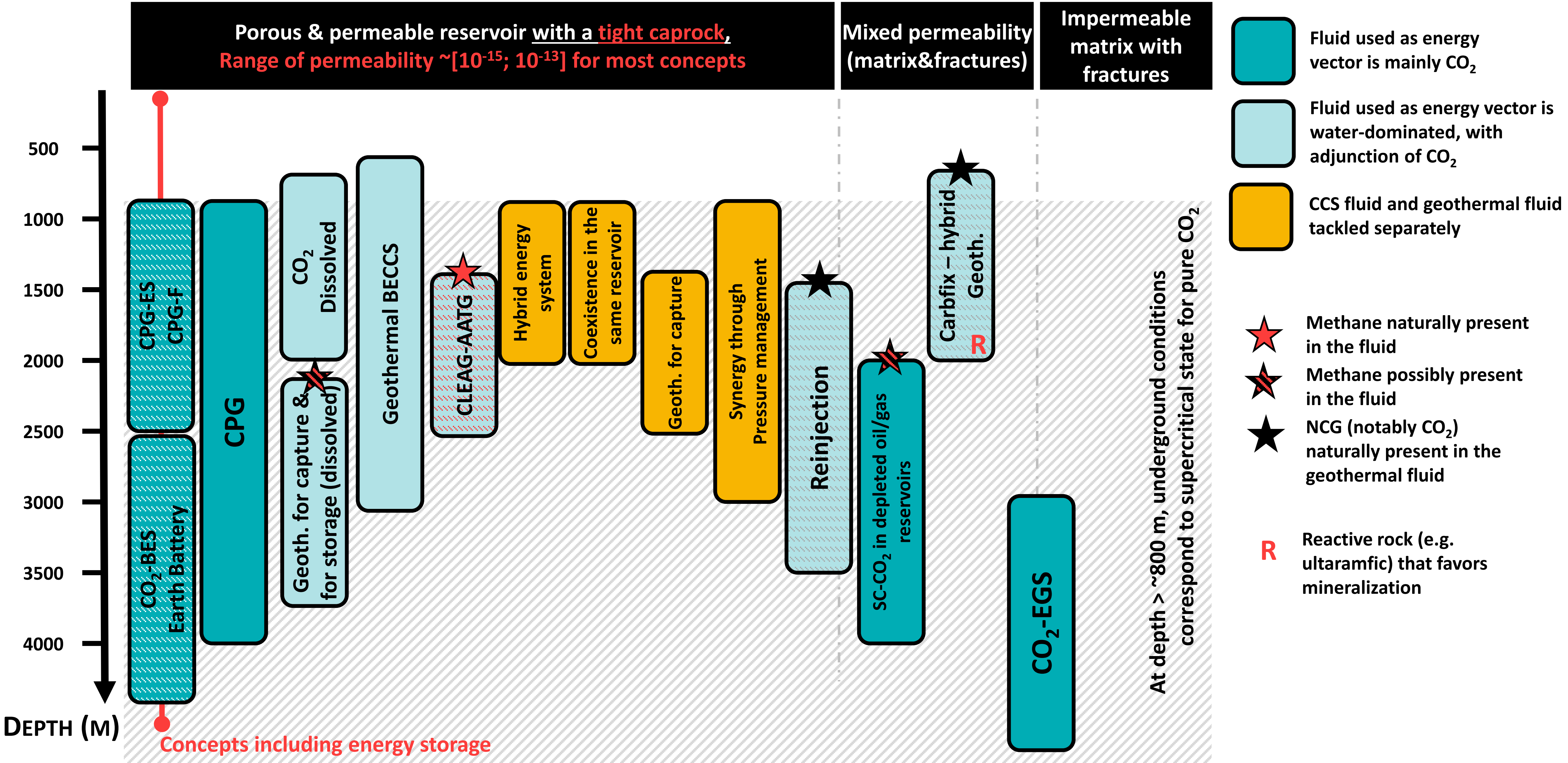


AN OVERVIEW
CO_2
CO_2 stored over 30 years (Mt)
Average annual storage (kt/y)
HIGH CO_2 STORAGE CAPACITY
LOW CO_2 STORAGE CAPACITY
100
3333
10
333
1
33
0
1
~3
10
~30
100
~300
Power capacity (MWe)
Or thermal capacity (MWth)
CO_2 storage
Carbfix – Non-hybrid
Coexistence in the same reservoir
CPG
CPG-ES
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)

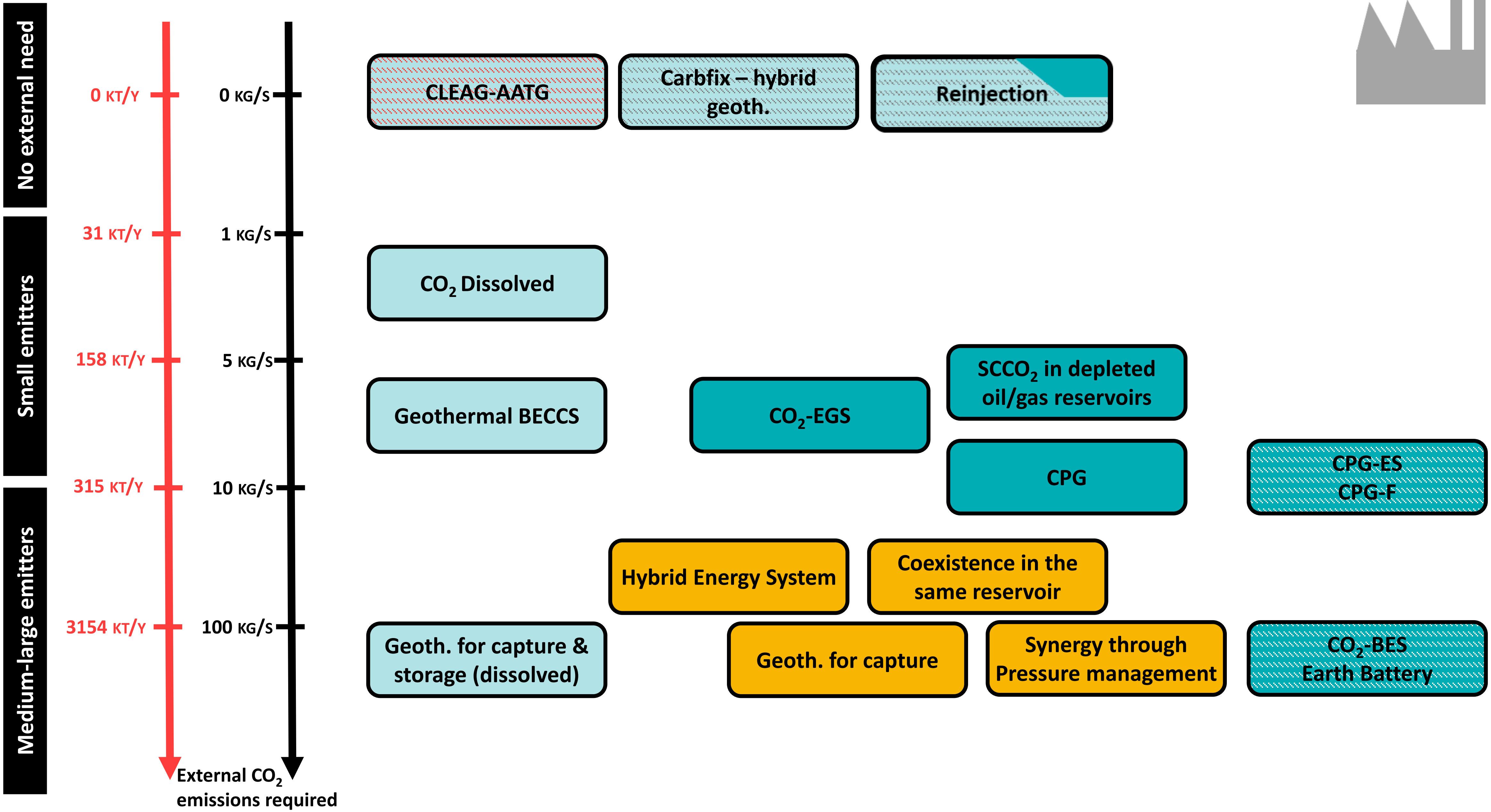
CLASSIFICATION ACCORDING TO FLUID CONTENT/CO_2 ORIGIN



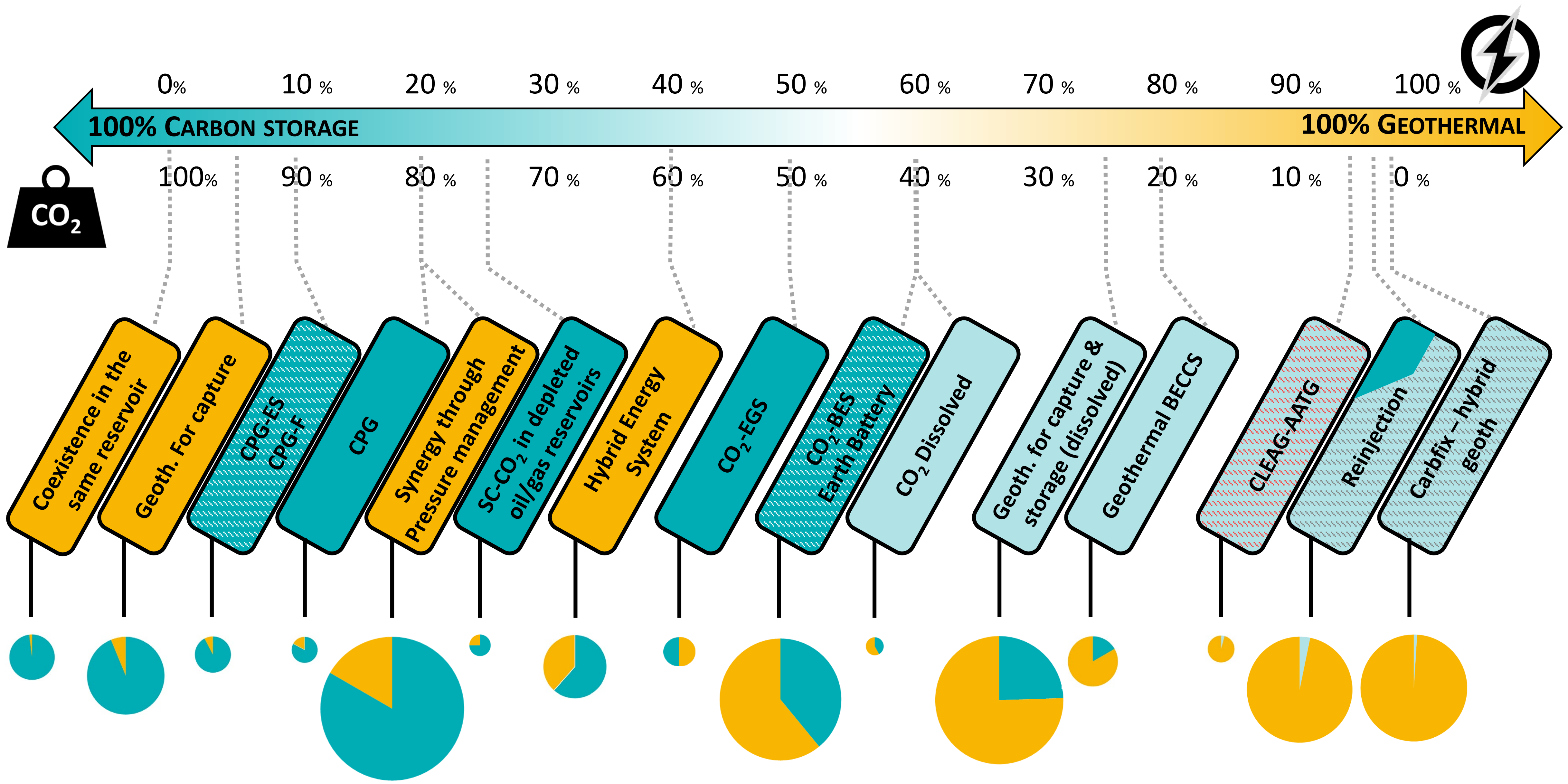
CLASSIFICATION ACCORDING TO UNDERGROUND FEATURES



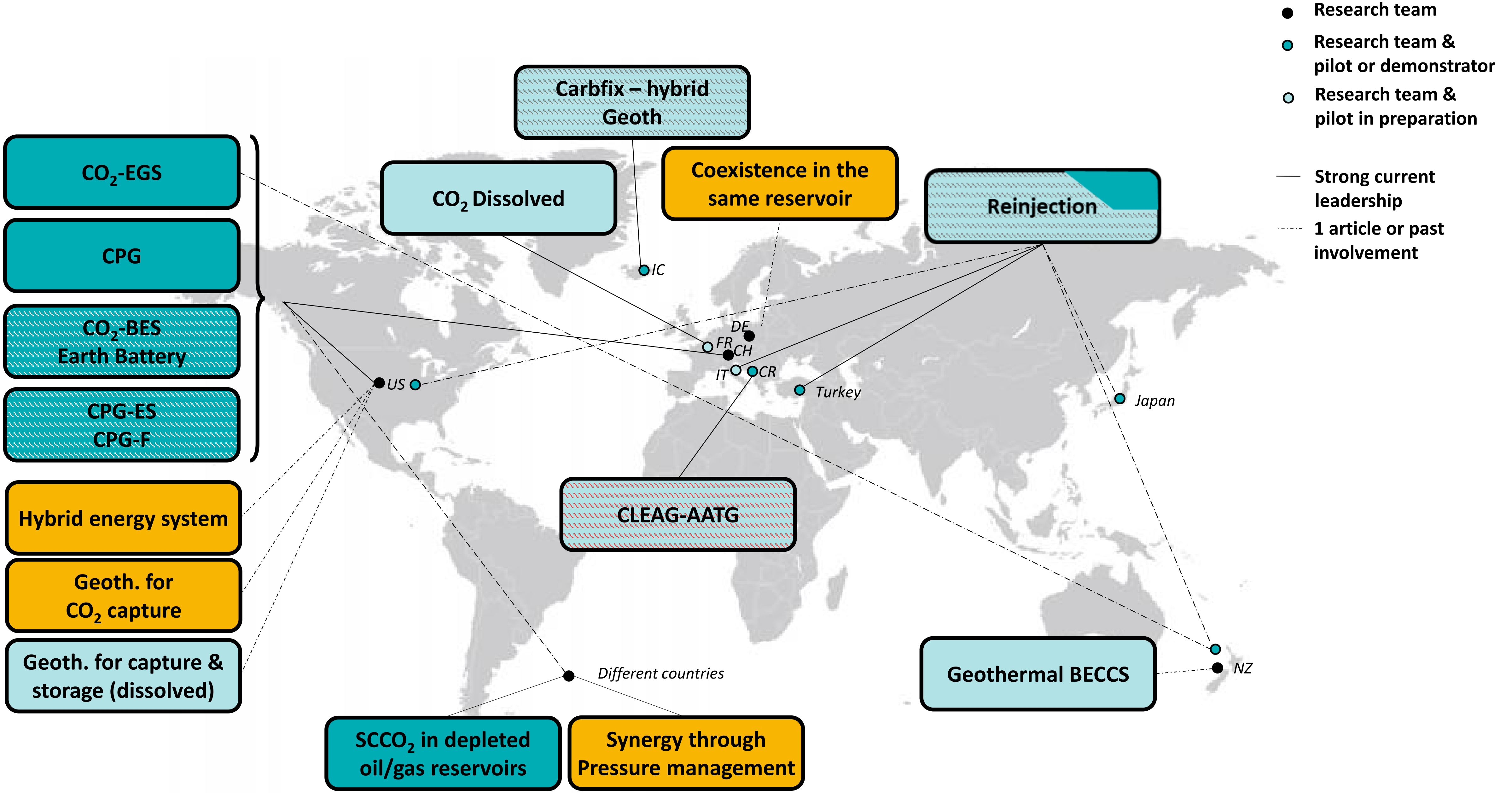
VIEWPOINT OF EXTERNAL EMITTERS



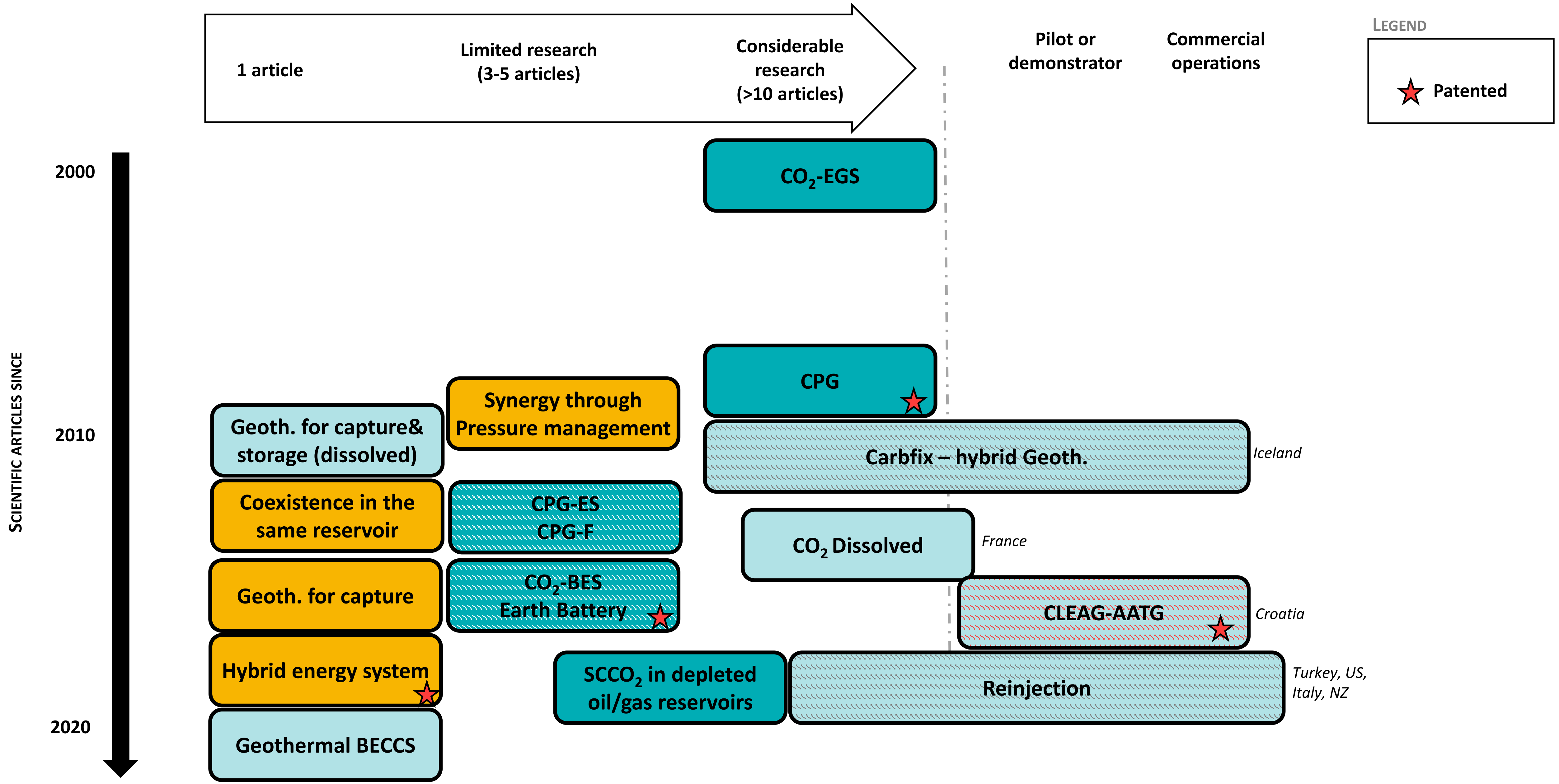
COMPARISON OF CONCEPTS ON THE CCS – GEOTHERMAL ENERGY SCALE



MAIN PROPONENTS



Overview of Research and path to commerciality



Summary of « main concepts » (1)

«Competitive» concepts that require similar geological features

CPG
- **CO_2-BES Earth Battery**
- **CPG-ES CPG-F**

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

Geoth. for capture and storage (dissolved)

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

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

Geoth. for capture

Info: geothermal heat can be used for capture process.

Hybrid energy system

Synergy through Pressure management

Coexistence in the same reservoir

Coexistence and synergy of heat mining & carbon 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 geoth.	*Takes benefit of the highly reactive nature of rocks in some geological contexts to target rapid mineralization*
CLEAG-AATG	*Addresses geological contexts where fluid contains methane. It optimizes fluid valorization and stores emissions*
SC-CO_2 in depleted oil/gas reservoirs	*Valorization of oil/gas reservoirs already exploited with CO_2 and extension of reservoir utilization with heat mining*
CO_2-EGS	*Extension of heat mining to fractured systems, with more complex surface and subsurface engineering*
Reinjection	*A solution to deploy near-zero geothermal exploitation in contexts where the geothermal fluid contains CO_2*

SUMMARY OF « MAIN CONCEPTS » (2)

«COMPETITIVE» CONCEPTS THAT REQUIRE SIMILAR GEOLOGICAL FEATURES

CPG & variants

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.

Storage of CO_2 dissolved in geothermal brine

HEAT MINING WITH INJECTION OF CO_2 IN DISSOLVED FORM FOR CO_2 STORAGE OBJECTIVE
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

Coexistence in the same reservoir

Synergy through Pressure management

COEXISTENCE AND SYNERGY OF HEAT MINING & CARBON 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 gth	*Takes benefit of the highly reactive nature of rocks in some geological contexts to target rapid mineralization*
CLEAG-AATG	*Addresses geological contexts where fluid contains methane. It optimizes fluid valorization and stores emissions*
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WP2

INFOGRAPHICS

COMPARISON OF CRITERIA

See the spreadsheet or Appendix 1

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Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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