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Integrating geothermal energy and carbon capture and storage technologies: A review

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ABSTRACT

Geothermal energy production and CO₂ capture and storage are two promising technological solutions for mitigating climate change and addressing the need for a sustainable global energy supply. In recent years, there has been a significant increase in the number of concepts that combine and integrate these technologies. A comprehensive literature review has been conducted, resulting in the mapping of fifteen hybrid concepts.

Certain concepts use supercritical CO₂ as the heat vector, some inject dissolved CO₂ into the geothermal brine, and others propose the separate use of distinct fluids for each purpose. Subsurface competition among the concepts is lower than could be initially expected: even if some concepts target similar formations at different depths and temperatures, a number of concepts are designed for specific subsurface characteristics. Besides, the concepts integrate differently into the value chains of CO₂ capture and storage and provide different energy services.

Most technologies are at low-to-intermediate maturity levels. Scaling up of these technologies would require addressing technical and non-technical challenges that share several similarities. Recommendations include promoting demonstration projects, fostering collaborative research, proposing incentives for CO₂ storage or emissions reduction, and advocating for a more flexible regulatory framework for hybrid applications.

Through a series of carefully designed infographics, this work aims at providing a valuable resource for researchers, policymakers, and industry professionals, facilitating a comprehensive and nuanced understanding of the full spectrum of hybrid concepts.

1. Introduction

According to IPCC [1], in order to limit detrimental consequences of human-induced global warming, it is necessary, by 2050, “to limit cumulative CO₂ emissions, reaching at least net zero CO₂ emissions, along with strong reductions in other greenhouse gas emissions”. It has long been acknowledged that geological CO₂ storage and geothermal energy (e.g. Ref. [2]) need to play a substantial role in order to achieve carbon neutrality and mitigate global warming. In Ref. [3], the potential contributions of geothermal energy and CO₂ Capture and Storage (CCS) to net emission reduction in 2030 are estimated each at between 1 and 2 GtCO₂-eq/y.

After short introductions of the geothermal and CCS technologies, the motivations that underlie the proposal to combine these technologies are summarized.

1.1. Geothermal energy

A diverse array of technologies has been developed to tap renewable geothermal energy resources that harness the earth’s internal heat. Geothermal energy exploitation is often referred to as “heat mining”. Among the prominent methods are geothermal heat pumps, doublets in hydrothermal systems, engineered/enhanced geothermal systems (EGS), and advanced geothermal systems (AGS). Geothermal heat pumps, which leverage stable ground temperatures to provide heating and cooling for buildings, and doublets in hydrothermal systems, which generally use naturally occurring hot water, are the most mature techniques and widely deployed globally. EGS target low permeability rock formations with limited natural fluid flow, so it is necessary to identify natural fracture systems that enable the fluid to circulate between the injection and production wells and enhance fluid circulation. Advanced geothermal systems address geological challenges with closed-loop systems that prevent fluid-formation interactions. In 2020, the total

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Abbreviations

ACRM	Active CO ₂ Reservoir Management	CPG-F	CO ₂ Plume Geothermal – Flexible
AGS	Advanced Geothermal Systems	DAC	Direct Air Carbon Capture
BECCS	BioEnergy with CO ₂ Capture and Storage	EGS	Engineered/Enhanced Geothermal Systems
BES	Bulk Energy Storage	EGR	Enhanced Gas Recovery
CCES	Compressed CO ₂ Energy Storage	EOR	Enhanced Oil Recovery
CCS	CO ₂ Capture and Storage	HDR	Hot Dry Rocks
CLEAG-AATG	Clozed Loop Energy AG developed by the company AATG	IEA	International Energy Agency
CPG	CO ₂ Plume Geothermal	IPCC	Intergovernmental Panel on Climate Change
CPG-ES	CO ₂ Plume Geothermal – Energy Storage	NCG	Non Condensable Gases
		NZIA	Net-Zero Industry Act
		SC-CO ₂	SuperCritical CO ₂
		TRL	Technology Readiness Level

worldwide geothermal power capacity rose to 15.7 GWe [4], with low global growth rates of 4 % per annum over the last 10 years.

Geothermal heat can then be used for electricity and/or heating/cooling purposes [5]. According to the IEA's net-zero 2050 report [6], the geothermal electricity capacity could reach 126 GWe in 2050. In parallel, heating and cooling are becoming an important driver of new developments in the geothermal sector. Despite these advancements, the widespread adoption of geothermal technologies faces several challenges. The upfront costs of drilling and reservoir development can be substantial, posing financial barriers, especially for smaller-scale projects. Additionally, the geological variability of subsurface conditions requires tailored approaches, adding complexity to project planning and implementation. Community engagement plays a crucial role, as local communities may express concerns about induced seismicity, water usage, or land impacts associated with geothermal projects. Addressing these socio-technical challenges is key to fostering sustainable growth and equitable deployment of geothermal energy worldwide.

1.2. CCS

CCS is a crucial technology for mitigating climate change, involving the capture of CO₂ from energy or industrial emissions sources, or directly from the atmosphere, followed by its permanent storage underground. Conceived in the 1970s, the initial projects primarily focused on enhancing oil recovery (EOR), and CO₂-EOR has played a pivotal role in advancing the implementation of CO₂ storage. The first dedicated industrial CO₂ storage project was initiated in 1996 at the offshore Sleipner Field in Norway, where it was demonstrated that CO₂ can be injected, up to approximately 1 Mt/y per well, and securely stored in deep saline aquifers. Since, the capacity of projects has grown substantially, reaching a potential of 111 Mt/y in 2021 [2]. Nevertheless, despite the remarkable expansion witnessed in recent years, the deployment of full-scale storage projects lags significantly behind the pace required to help achieve the net-zero objectives outlined in the Paris Agreement [2].

Large-scale CCS deployment relies on injecting CO₂ in its supercritical form, i.e. having a gas-like behaviour with low viscosity but with the density of a liquid, which enables a combination of ease of injectivity and high storage capacity. 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. Due to its density lower than that of mineralized water under typical reservoir conditions, CO₂ migrates upward due to buoyancy, necessitating an impermeable caprock for containment. In the initial phases of CCS projects, structural/stratigraphic trapping is the predominant mechanism. As time progresses, the proportion of CO₂ dissolved in native brine increases, leading to a rise in solubility/dissolution trapping mechanisms; the residual/capillary trapping also increases. Over the long term, mineral trapping becomes increasingly

significant. The ratio of these mechanisms is influenced by factors such as injection duration, the state of injected CO₂, and geological conditions (permeability, caprock characteristics, etc.). The level of risk decreases as trapping mechanisms transition to solubility/dissolution and further diminishes when mineral trapping takes precedence. The emphasis on this point is crucial for discussing the technologies introduced hereafter and making distinctions among them.

1.3. Rationale for combining geothermal and CCS technologies

The rationale behind the interest in hybridization is multi-faceted, encompassing various conceptual justifications:

Economic Advantages: Both the exploitation of geothermal energy and CCS come with considerable costs. Mutualization of investment (including exploration) and operation costs, and deriving dual revenues from a single project, can significantly enhance economic performance. These considerations could prove pivotal in advancing the broad adoption of CCS and, to a lesser extent, geothermal energy.

Optimization of subsurface resources: Certain methods of heat mining and CO₂ storage necessitate similar geological features, such as high porosity and sufficient permeability. Rather than fostering competition among various uses of the same resource, these concepts seek synergies for collective and efficient application.

Moreover, supercritical CO₂ (SC-CO₂), due to its high mobility [7,8], provides an alternative for tapping into geothermal energy from reservoirs that are less permeable or less consolidated. As a result, the range of formations suitable for deploying hybrid technologies might be more extensive.

At intermediate depths or in specific geological conditions, deploying CCS with SC-CO₂ could prove impractical. In such cases, technologies relying on dissolved CO₂ would be more suitable.

Enhanced performance and efficiency: SC-CO₂ used as a heat vector holds the potential to significantly enhance the efficiency of heat mining processes. The advantages of using SC-CO₂ as a heat vector for EGS (rather than water/brine) have been highlighted by Brown [9], and then further discussed in numerous studies. The main comparative features of CO₂ vs. water as geothermal working fluids [10] are as follows.

- Enhanced flow due to the lower viscosity of CO₂. Despite its lower density, the favourable ratio of density to viscosity generally favours CO₂ over brine in most cases.
- CO₂ exhibits a lower mass heat capacity (kJ/K/kg) compared to water. Nevertheless, this drawback is compensated by achieving higher extraction rates for CO₂ due to its increased mobility in most scenarios.
- The compressibility and expandability of CO₂ lead to a substantial density contrast between cold CO₂ (dense, heavy) injected into the well and hot CO₂ (less dense) extracted from the production well. This creates a significant buoyancy force, reducing power

consumption for circulation and pumping when compared to a water-based system of similar scale - a phenomenon known as the thermosiphon effect.

- From a chemical standpoint, SC-CO₂ does not yield ionic dissolution products, mitigating the mineral dissolution/precipitation challenge in the absence of water. However, practical considerations in the field may counterbalance theoretical advantages.

In systems where CO₂ is injected in dissolved form within geothermal brine, this advantage in performance and efficiency becomes less pronounced. The geothermal system behaves mainly as a water-driven system, but the adjunction of dissolved CO₂ can, in some cases, increase thermo-hydrological performance (pH decrease might avoid clogging and/or open porosity in carbonated reservoirs).

1.4. Scope

The CCS and geothermal energy concepts considered in this study exhibit at least one of the following characteristics: i) both systems employ the same working fluid, where either SC-CO₂ directly serves as the heat vector or CO₂ is injected into the circulating geothermal water; ii) both occur in the same formation; iii) both use shared subsurface installations, including wells; iv) geothermal energy is used to meet energy requirements in CO₂ capture facilities.

Concepts outside the scope of the review: Concepts employing CO₂ as a heat vector in closed systems (e.g. Refs. [11–13]) lie outside the scope of this study. In these systems, CO₂ is deliberately isolated from direct interaction with the subsurface, leading to the absence of CO₂ storage at the end of operations. Compressed CO₂ energy storage (CCES) [14] was not included in the present review since it does not rely on geothermal exploitation. THE METHARC concept [15] was not included because it primarily focuses on H₂ production and does not involve CO₂ handling at the surface.

1.5. Ambition and novelty

This review is the first of its kind, and consists of an examination of all the concepts/technologies that combine and hybridize features of CCS and geothermal energy supply (electricity, heat) or energy storage. Where previous reviews exist they focus on specific concepts, e.g. with supercritical CO₂ ([16,17]) or on projects that reinject non condensable gases (NCG) [18].

This review explores the complexity of emerging technologies, where numerous concepts are being developed in parallel. At first glance, it is difficult to discern the level of overlap or how distinct these innovations truly are. A number of key questions arise: are these technologies competing? For a specific site, how to determine which is best suited? Are several viable, or is one clearly superior? For decision-makers—whether regional planners or research funders—prioritizing among these concepts is a challenge. Is it already possible to foresee which technologies will become dominant, which will remain niche, and which may never emerge? Understanding these uncertainties is essential for shaping future strategies.

This review distinguishes itself by addressing the full spectrum of hybrid concepts, rather than focusing on isolated subsets as in previous studies, based on an analysis of over 200 articles. Beyond its comprehensive scope, it provides a broader perspective by positioning each concept within the value chain, highlighting how they address distinct requirements. This work offers a valuable contribution for researchers, policymakers, and industry professionals, enabling a rapid understanding of the landscape to guide further exploration with confidence and ensure no critical aspect is overlooked—a resource previously unavailable in this domain.

1.6. Method

This review was conducted using standard bibliographic research tools (Google Scholar, Web of Science, Rabbit), with particular attention given to references cited in each article and the use of carefully selected and expanded keywords to ensure comprehensive coverage. Keywords were extensively combined and broadened to maximize exhaustiveness. Additional searches were performed online using conventional search engines to identify concepts not covered in scientific publications, such as the CLEAG-AATG concept. In cases of uncertainty or missing data, interviews were conducted, notably regarding CLEAG-AATG and to clarify the progress of various demonstrators. Two brainstorming sessions involving all authors facilitated the creation of visual syntheses to effectively and concisely communicate the results of this extensive review. The results of this work provide a considerably broad overview of the state of the art as of 2024, based on the available published information. However, a limitation of this approach is that certain isolated concepts, referenced with different keywords or not readily published/accessible, may have been inadvertently overlooked. The figures presented have been meticulously verified, with careful attention to providing ranges that accurately represent the values most commonly reported. Outliers or extreme values occasionally found in isolated studies have been excluded when deemed unrepresentative. It is important to acknowledge that errors or debatable choices may still exist. Consulting the original sources referenced in this review is essential in case of doubt or for readers who wish to delve deeper and understand the choices made in this review. The goal is to provide a quick overview with order-of-magnitude estimates, but it was not feasible to present every detail or explain the rationale behind each selected range.

2. Variety of integrated technologies

In this study, three main groups of concepts have been identified, based on the fluid used as the heat vector (see Fig. 1 and Table 1).

- Concepts using external SC-CO₂ as a heat vector to extract heat from subsurface reservoirs (section 2.1; dark blue on Fig. 1). Note: external CO₂ refers to CO₂ that originates from capture facilities as opposed to from geothermal formations.
- Concepts generating geothermal energy with water-dominated fluids, co-injecting CO₂ (typically in dissolved form) during the process. Two main origins are possible for the injected CO₂: from an external source (section 2.2; light blue on Fig. 1) or from the separation of NCG associated with the production of geothermal fluids (section 2.3; light blue circled by red dashed line on Fig. 1)
- Concepts exhibiting hybridization between geothermal energy production and CCS to a lesser extent, involving operations in reservoirs with indirect interaction between geothermal energy extraction and CO₂ storage through pressure management, shared subsurface installations like wells, or using geothermal energy for CO₂-capture facility needs (section 2.4; grey on Fig. 1).

The concepts are presented succinctly. A more comprehensive description of each concept, along with a detailed table outlining key characteristics, can be found in Ref. [19].

2.1. Using external SC-CO₂

2.1.1. CO₂ plume geothermal (CPG)

Description: This concept (Fig. 2-a, Table 1) employs SC-CO₂ as a heat vector for geothermal energy extraction in traditional porous and permeable hydrothermal reservoirs. Known as “CPG” (CO₂ plume geothermal), the system was initially proposed by Randolph and Saar in 2011 [7,20,21]. The system is initialized with CO₂ injection over months to years to create the CO₂ plume. Once a SC-CO₂ plume encompasses

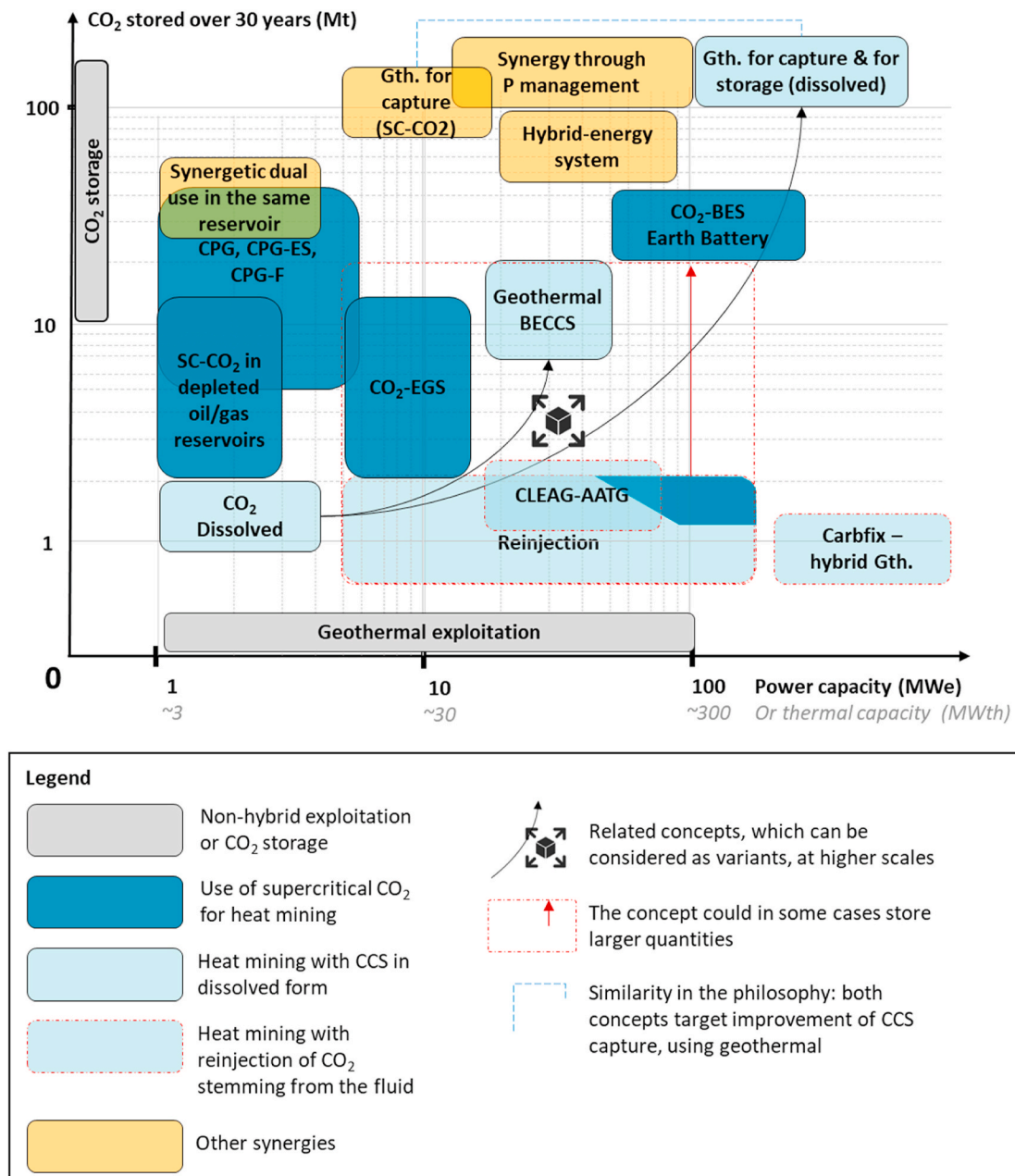


Fig. 1. Concept overview based on CO₂ Storage Capacity (Ordinate) and Power Capacity (Abscissa). Some concepts focus on electricity production, while others prioritize heat generation. To address the differing valorization of electricity and heat, a translation ratio of 3 has been applied, reflecting an estimated market value for MWhth compared to MWe (see abscissa). CPG: CO₂ plume geothermal. -ES: energy storage. -F: flexible. CLEAG-AATG: Clozed Loop Energy AG developed by the company AATG. BES: bulk energy storage. BECCS: bioenergy with CCS. Gth: geothermal energy extraction.

injection and production wells, geothermal exploitation begins. Cold CO₂ is injected, and hot CO₂ is pumped up for power generation using a CO₂-compatible turbine or heat exchanger. New external CO₂ is continuously co-injected to compensate fluid losses in the reservoir. Studies estimate the make-up CO₂ to be around 5–10 % of the total flow, but there is no field experience. The quantity of CO₂ stored corresponds to the initial CO₂ necessary for system initialization, as well as the continuous CO₂ recharge that compensates loss. CO₂ storage is consequential, with potential for several tens of Mt of CO₂ storage per project. CPG is deemed more efficient than water-driven systems in many cases. Its replicability potential is assumed to be wide, especially in low-permeability conditions unsuitable for conventional geothermal brine exploitation [7].

From concept to demonstration: Significant scientific progress has

been achieved spearheaded primarily by American teams and ETH-Zurich, including a patent in 2012 [22]. Since the first articles introducing the concept [7,20,21], several studies further discuss the design and energy efficiency [23–28], the impact of geological conditions [29, 30], or technical-economic performance [31–34], as well as life cycle assessments [35]. Studies with promising results have been proposed for different countries (e.g. for India [36,37], for Germany [38], for Mexico [39], for Indonesia [40], for Switzerland [41], for Aquistore in Canada [42,43]). The concept of CO₂ extraction has been tested in 2015 at the SECARB Cranfield site (Mississippi, USA [44]) at a depth of 3.2 km, but the thermosiphon effect was not sustainable contrary to model predictions [45]. To the best of available knowledge, no other operational pilot or demonstrator exists in 2024.

Critical perspective: This method shows promising potential and

Table 1

Key features of each technology. The values provided are approximate and aim to represent the prevalent and commonly available ranges, see more details in Ref. [19]. (*): The figure “18” corresponds to the assumption of total reinjection for a power plant such as Kizildere but currently less than 10 % of produced CO₂ is reinjected, so 1.8 Mt CO₂ is currently more realistic.

Technology	Depth (km)	Temperature (°C)	Number of wells	Flow rates (kg/s)	Thermal (th) or electrical (e) power output (MW)	CO ₂ storage over 30 years (Mt CO ₂)
CPG	1–4	80–200	2–5	SC-CO ₂ : 100-300	10-60 MWth, or 1–6 MWe	5–30
CO ₂ -EGS	3–6	160–300	2–5	SC-CO ₂ : 100-300	30-90 MWth, or 5–15 MWe	2–15
Heat mining with SC-CO ₂ in depleted oil/gas reservoirs	2–4	100–150	2-many	SC-CO ₂ : 20-100	1-3 MWe (higher values might be reachable with upscaling)	2–16
CPG-ES/CPG-F	~2.5 And 1–2	~100	~7	SC-CO ₂ : 100-600	1–2.5 MWe	20–45
Earth battery	3–5	130–200	Several tens (e.g. 42–75)	SC-CO ₂ : ~2000 Brine: 3000–6000	50-300 MWe	50–160
CO ₂ -Dissolved concept	1–2	40–80	2	Brine: 50-100 CO ₂ (dissolved): 1-5	4-10 MWth	1–2
Geothermal-BECCS concept	0.5–3	160	Not mentioned 10-20 (assumed)	Brine: 400-1200 CO ₂ (dissolved): 7–20	Not mentioned 20-50 MWe (assumed)	7–19
CCS-driven concept	3	150	30	Brine: 2200 CO ₂ (dissolved): 120	250 MWe and 500 MWth	120
CO ₂ reinjection concepts	1.5–3.5	150–300	2-several tens	Brine: 12-1000 CO ₂ (dissolved): 1–30	5-200 MWe	CO ₂ avoided 0.3–18*
Carbfix concept	0.7–2	200–300	2-several tens	Brine: ~1000 CO ₂ (dissolved): ~1	~300 MWe	CO ₂ avoided 0.3–1.2
CLEAG-AATG concept	1.8–2	100–120	~8	Brine: ~320 CO ₂ (dissolved): ~1.8	~12 MWe + 80 MWth	CO ₂ avoided ~1.7
Synergetic use through pressure management	1–3	50–150	~5–10	Brine: 50-250 SC-CO ₂ :100-500	50-500 MWth	100–500
Synergetic dual use in the same reservoir	~1	~50	At least 2	Brine ~20 SC-CO ₂ ~50	Not mentioned	~50
Hybrid energy system	1–2	~90	~14	Brine: ~271 SC-CO ₂ :~57; 114	21-75 MWe (attributed to geothermal contribution)	57–114
Geothermal energy used for capture	1.5–2	~150	~7	Brine: ~314 SC-CO ₂ : ~150	~10 MWe (savings attributed to geothermal)	~150

ambitions that warrant further exploration. However, evaluating it with high flow rates yields overly optimistic perspectives, while variable CO₂ flow requirements and compliance with the CCS directives pose significant risks and costs. Many cited studies originate from proponents with commercial interests, calling for critical interpretation of their conclusions. It now seems necessary to test its operational viability through a demonstrator.

2.1.2. CO₂-EGS

Description: The CO₂-EGS concept (Fig. 2-d, Table 1) employs SC-CO₂ as a heat vector to extract heat from deep fractured rock formations (depth 3–6 km, temperature 160–300 °C), mainly for electricity production. Introduced by Brown [9], this technique involves deep drilling, hydraulic, thermal, or chemical stimulation to enhance permeability, and CO₂ injection. Unlike CPG, CO₂-EGS relies on fractures rather than matrix porosity, limiting overall storage capacity. The extracted hot CO₂ is used in a CO₂-compatible turbine to produce electricity or through a heat exchanger. CO₂-EGS demonstrates potential for increased thermal extraction rates compared to water-based systems. Continuous CO₂ injection compensates for fluid loss (estimated around 5–10 % of the total flow) with beneficial CCS consequences. The quantity of stored CO₂ will heavily rely on site conditions, including fractures (and possibly matrix) porosity and permeability. At this stage, a tentative estimate suggests a range of 2–15 Mt of CO₂ over a 30-year period (this estimate corresponds to a common range of values deduced from different articles), acknowledging current uncertainties.

From concept to demonstration: The concept has been presented [9,46–49], and then further investigated by academic and research laboratory communities. Scientific studies provide notably insights into

geochemical phenomena or CO₂-rock interactions [50–53], into thermo-hydro-mechanical phenomena [54,55], into operation design [56,57]. These studies underscore the multitude of technical challenges that persist, particularly in the realms of thermo-hydro-mechanical and geochemical understanding and modelling. Main realistic CO₂-EGS case studies investigated in the state of the art (Fenton Hill in US [9] Soultz-sous-Forêts in France [46,48,50,51,58,59], Groß Schönebeck in Germany [56,60], Acoculco in Mexico [39], Habanero in Australia [61]) might provide rather optimistic performance indicators. To the best of available knowledge, there are currently no pilots or demonstrators for this concept. The only tests found in the literature took place in Japan (Ogachi and Hijiari) where CO₂ was injected in the dissolved form in water in hot dry rocks (HDR being a sub-concept of EGS) to study reactivity [62]. Limited economic analysis exists for the concept, with one sole study [63].

Critical perspective: Case studies in the state of the art often present overly optimistic or unrealistic figures. While Enhanced Geothermal Systems (EGS) using water still face numerous challenges, introducing CO₂ as a working fluid is likely to introduce additional complexities. Moreover, CO₂-EGS requires a structure capable of retaining the CO₂ plume and must comply with the CCS directives. The implementation of a demonstrator in the short term, and ultimately the global replication of the concept, appears to be a highly complex and challenging task.

2.1.3. Heat mining with SC-CO₂ in depleted oil/gas reservoirs

Description: CO₂ has been widely used to assist/enhance hydrocarbon production in CO₂ enhanced oil recovery (CO₂-EOR) and CO₂ enhanced gas recovery (CO₂-EGR). The addition of CO₂ changes the viscosity of the remaining oil and increases the overall pressure, and

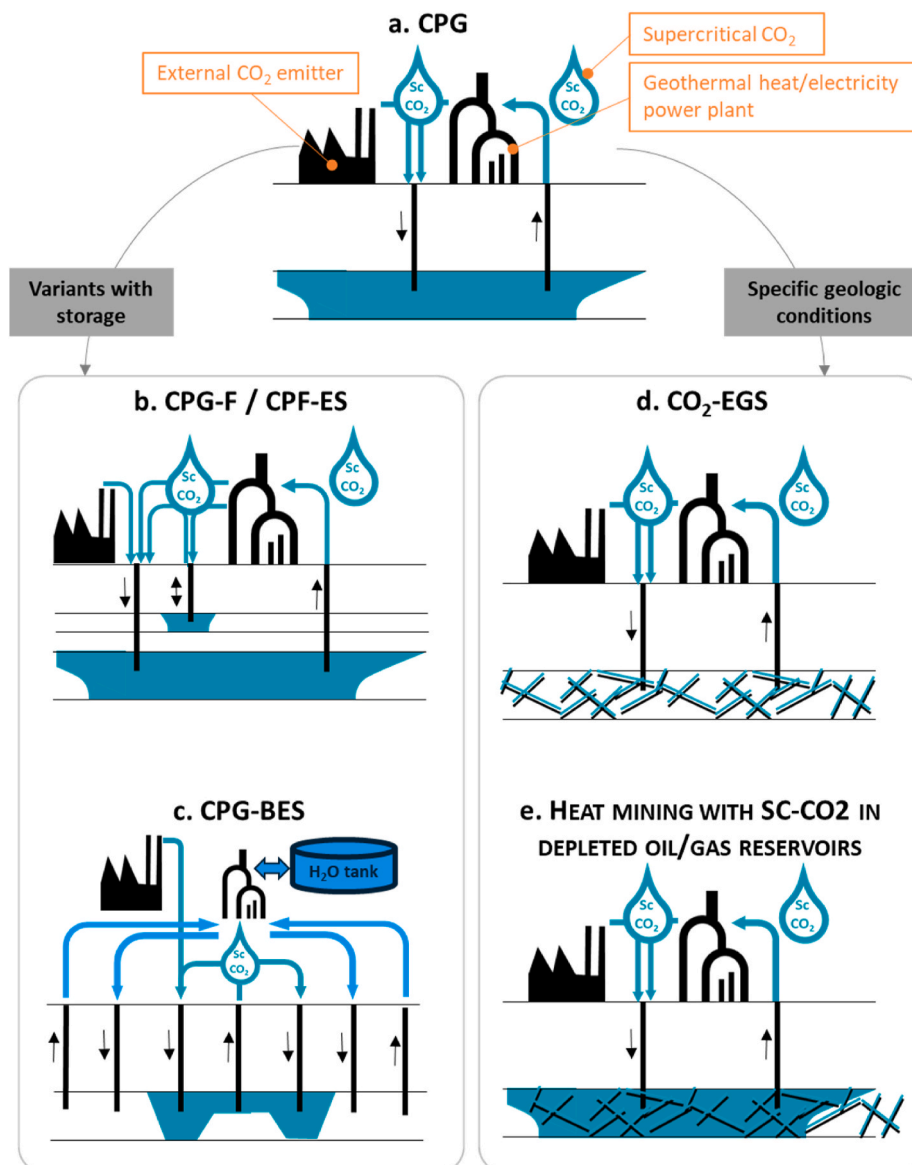


Fig. 2. Simplified schemes of concepts using external SC-CO₂ in vertical cross-sections, showing depths and the different subsurface layers. The scales are not intended to be representative. The blue colour corresponds to water. The turquoise colour corresponds to SC-CO₂. a. CPG (CO₂ plume geothermal). b. CPG-F (-flexible) or CPG-ES (-energy storage). c. CPG-BES (bulk energy storage) - For concept c, the primary design features concentric circular rings surrounding the central well (with tens of wells). d. CO₂-EGS (enhanced geothermal system). e. Heat mining with SC-CO₂ in depleted oil/gas reservoirs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

thus facilitates (oil/gas) production at the end of the exploitation period when the reservoir is partly depleted. These techniques are out of the scope of the present study, since there is no hybridization with geothermal energy extraction, but novel techniques have been proposed to progress the concept and to use existing facilities in depleted hydrocarbon reservoirs to co-produce geothermal energy with SC-CO₂ as a heat vector (Fig. 2-e, Table 1). After primary recovery of the gas, CO₂ 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 CO₂ as a heat vector. Different designs and/or sequential site-dependent exploitations might be possible (e.g. Refs. [64–66,66–69]).

From concept to demonstration: This concept is at the scientific literature stage. The widespread use of CO₂ injection in various geological formations underscores a promising trajectory towards feasibility. Natural gas reservoirs, in particular, exhibit inherent advantages for CO₂ storage given that fossil gas has been trapped for

geological timescales, which ensures sealing integrity. Additionally, the comprehensive understanding of geological conditions and the presence of pre-existing wells in these reservoirs might facilitate implementation processes and limit investments costs.

No pilot exists to the best of available knowledge and a number of specific challenges need to be addressed, such as the effects of residual methane, of H₂S and of water saturation, as well as the importance of the sequential design and possible salt precipitation and corrosion issues.

Critical perspective: This concept remains deployable on a case-by-case basis, depending on the reservoir, timing, and local heat demand. A potential concern for hybridization in natural gas reservoirs is the integrity of shut-in legacy wells, which could become leakage pathways for CO₂. Additionally, residual methane and oil could contaminate the produced CO₂, leading to fouling and possible corrosion of surface equipment.

2.1.4. CPG-energy storage (CPG-ES) or CPG-flexible (CPG-F)

Description: An innovative variant of the CPG concept (Fig. 2-b, Table 1) is CPG-ES (energy storage [70]) or CPG-F (flexible [71]). Beyond its primary function, it serves as a versatile tool for electricity storage, facilitating the balancing of supply and demand—especially valuable for mitigating the intermittent production of renewable energy sources like wind or solar on a daily basis. When tapping into geothermal energy within deep aquifers using SC-CO₂ as a working fluid, the energy consumption stems from reinjection of the CO₂ at depth. This process results in a reduction of gross power production due to parasitic energy requirements, leading to a lower net energy production. Different studies [70–72] propose a strategy to time-shift the load necessary for CO₂ deep reinjection. In periods of high electricity demand, the high-pressure turbine is employed to exploit CO₂, but reinjection at depth is deferred. Only a minimal parasitic load is needed to temporarily inject and store CO₂ into a shallow aquifer. Conversely, when the balance between electricity demand and supply shifts, electricity is drawn from the grid to inject CO₂ into the deep aquifer.

From concept to demonstration: This class of concept remains

theoretical at this stage. It presents practical complexity, requiring two suitable formations for CO₂ storage.

Critical perspective: This class of concepts appears highly sophisticated and thus difficult to implement, even though it is theoretically promising. CPG alone already presents significant practical challenges, and in the short term, it seems crucial to first demonstrate the CPG concept.

2.1.5. Multi-fluid geothermal energy system, also called “earth battery”

Description: Several studies [73–76] have proposed a ground-breaking concept situated in a permeable reservoir formation at depths ranging from 3 to 5 km. This concept (Fig. 2-c, Table 1)s.

From concept to demonstration: The concept remains theoretical. It appears particularly complex and thus hardly practicable, even if theoretically attractive.

Critical perspective: The scale of the concept (demanding numerous wells, high flow rates, and complex fluid management) surpasses the current capabilities of subsurface engineering. In the short term, such designs are impractical. Demonstrating the feasibility of the

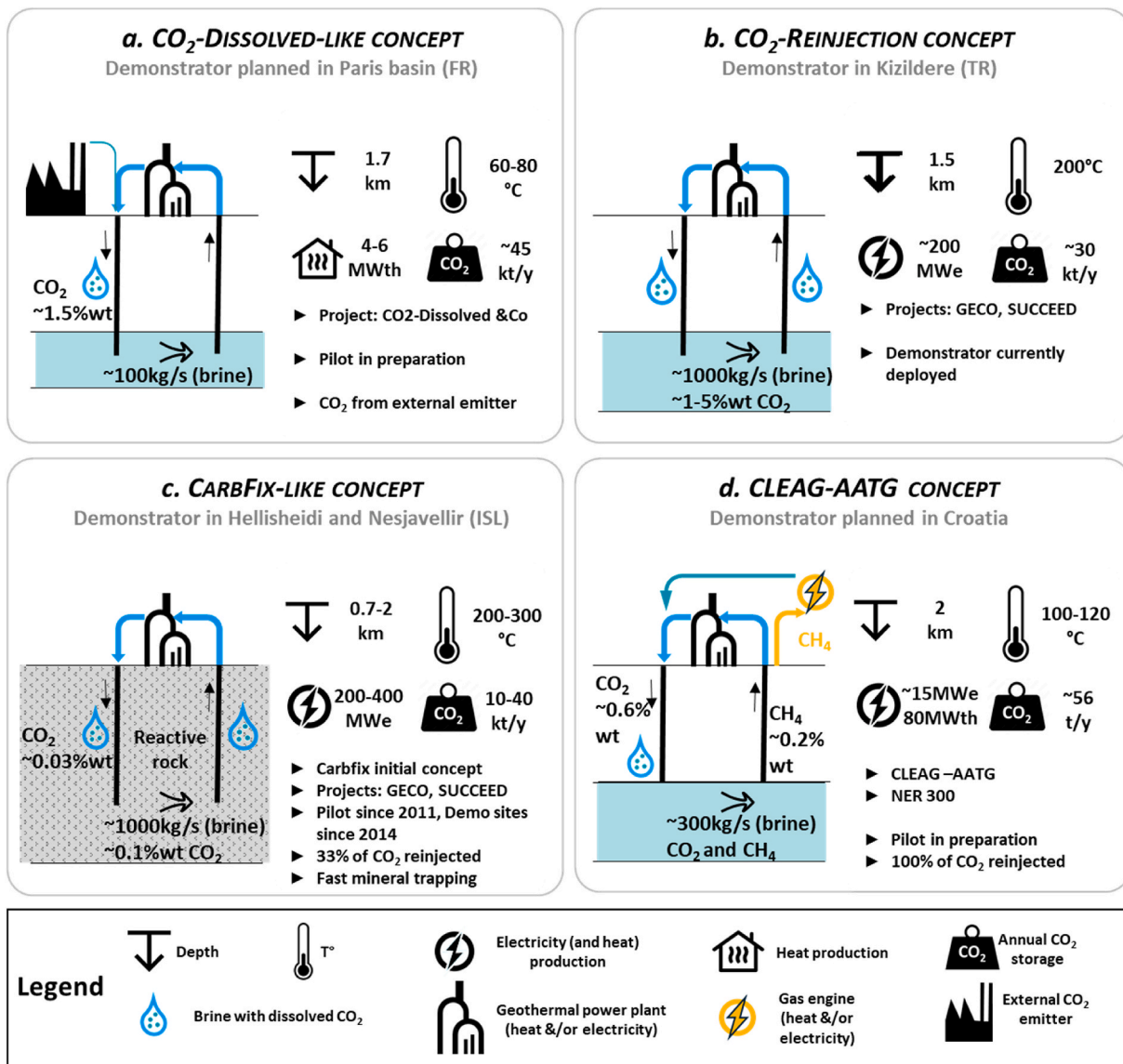


Fig. 3. Simplified vertical cross-sections for main operational/planned demonstrators, generating geothermal energy with water-dominated fluids, co-injecting CO₂ (typically in dissolved form) during the process. a. CO₂-Dissolved-Like concept. b. the Turkish site as the more advanced demonstrator for CO₂ reinjection demonstration, c. Icelandic sites for the Carbfix concepts, and d. The Cleag-AATG concept. Figures give estimates corresponding to the demonstrators. These figures should be considered indicative only and the scales are not representative.

CPG technology on a smaller scale is a critical first step before pursuing larger, speculative implementations.

2.2. Injecting external dissolved CO₂

2.2.1. CO₂-dissolved concept

Description: The concept is schematically illustrated in Fig. 3-a, and key features are provided in Table 1. It is based on a conventional geothermal doublet in a hydrothermal aquifer at depths ranging from around 1 to 2 km, with brine serving as the fluid vector, alongside the simultaneous storage of CO₂ dissolved in the reinjected brine [77–79]. The target temperature range for the geothermal resource is 40–80 °C, aimed at heat production. Since CO₂ is injected entirely in the dissolved form, and considering the solubility limit of CO₂ in brine, this approach is suited to small-scale CO₂ industrial emitters (approximately <150 kt/y), even though larger emitters (ca. 150–300 kt/y) are also a possible target. The potential mineralization process is accelerated compared to the injection of CO₂ in supercritical phase. Furthermore, using CO₂ in dissolved form offers significant advantages in terms of storage safety, including no pressure buildup in the aquifer (as for a standard geothermal doublet) and limited CO₂ leakage risk due to a lack of buoyancy (no gas phase in the reservoir).

From concept to demonstration: This concept was initially proposed in France in 2013 [80]. Current efforts are focused on preparing a first demonstrator in France.

Critical perspective: Given the limited amount of CO₂ sequestered per well, dissolution-based storage results in high costs per ton stored, posing challenges to its economic viability, particularly for making CO₂ capture cost-effective. A demonstrator is needed to tackle practical challenges, with proper design being critical.

2.2.2. Geothermal BECCS concept

Description: In 2022, Titus et al. [81,82] introduced a concept called BECCS (bioenergy with carbon capture and storage) that integrates a biomass power plant as the CO₂ emitter. This approach combines geothermal heat with biomass energy to boost power generation, primarily for electricity production. The CO₂ emitted by the plant is captured, dissolved in geothermal brine, and stored in the geothermal reservoir.

This concept can be seen as a more specialized version of CO₂-Dissolved, utilizing geothermal energy to support the biomass power plant and capturing its CO₂ emissions. It operates on a larger scale, employing multiple doublets, higher-temperature reservoirs (e.g. 160 °C as noted in the article), and greater flow rates, resulting in increased geothermal energy production and CO₂ storage (Table 1).

From concept to demonstration: This concept is recent and theoretical.

Critical perspective: If dissolved CO₂ injection proves successful, the Geothermal-BECCS concept could offer significant potential. Multi-energy systems efficiently combine geothermal heat and biomass for CHP production, with CO₂ readily available on-site. In the short term, validating the CO₂-Dissolved technology is a key step before advancing to this integrated approach.

2.2.3. CCS-driven concept

Description: Another concept that can be viewed as a special variant of CO₂-Dissolved, but differing in scale, was presented in 2013 [83]. Once again, it consists in injecting CO₂ from an external emitter and in dissolved form using the reinjection well of a geothermal doublet, and using the brine for energy production. The key philosophy behind this concept is to improve the performance of CCS capture facilities by using geothermal heat extraction to compensate for the additional energy required for capture and using geothermal brine as a vector for CO₂ storage. The design of the concept is adapted to meet the needs of the CCS facility. Considering a captured CO₂ flux of 116 kg/s, the geothermal water flow (~2200 kg/s) is tailored to solubilize all the

captured CO₂, necessitating 30 geothermal wells (Table 1). The geothermal fluid, assumed to contain methane (0.4 % by weight), produces around 250 Mwe (Table 1), while the geothermal heat provides approximately 500 MWth, slightly exceeding the energy required for the CO₂ capture and storage process.

From concept to demonstration: The concept is recent and theoretical. There is limited information and debate on the feasibility of this concept. The volumes of water and reservoir space required for such large quantities of dissolved CO₂ are substantial, which raises feasibility concerns.

Critical perspective: The concept seems impractical due to the large water and reservoir volumes needed to dissolve the substantial amount of CO₂. Moreover, assuming high methane content near a capture facility is overly optimistic.

2.3. Reinjecting dissolved CO₂ in the geothermal fluid

2.3.1. CO₂ reinjection

Description: This concept involves reinjecting CO₂ emitted during geothermal exploitation. When operating a geothermal doublet, the native fluid pumped may contain NCG such as CO₂, NH₃, N₂, CH₄, H₂S, and H₂, which might be released into the atmosphere. In certain geological contexts, such as Türkiye, Iceland, Italy, and New Zealand, the geothermal fluid has a significant NCG content, negatively impacting greenhouse gas emissions of the geothermal production. The global average emission factor for geothermal projects is 121 g/kWh [84], but in several sites in Türkiye and Italy, greenhouse gas emissions from geothermal power plants can exceed 500 g/kWh and, in some cases, surpass emissions from coal-fired power plants [85,86]. To address this, reinjection of produced CO₂ back into geothermal fields has been proposed for sites with high NCG content [87,88]. The first option is to reinject NCGs entirely dissolved in the geothermal fluid. This enhances solubility trapping, prevents geomechanical damage due to overpressure, and reduces the risk of gas leakage from the reservoir. For geothermal fluids with high NCG ratios, it is not always feasible to dissolve all NCG due to the solubility limit. In such cases, either a liquid brine-CO₂ mixture can be reinjected [89], or CO₂ can be reinjected in supercritical form into a separate well.

From concept to demonstration: In the past, NCG reinjection has already been tested for geothermal reservoirs in a few fields including Hijiori, Ogachi (Japan) in 2002, Coso for H₂S since 1989 (USA), and Puna for H₂S since 1993 (Hawaii) [18,89]. Currently, 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.

Apart from the Carbfix project (presented in section 2.3.2, as a specific case), several initiatives have been proposed in recent years to demonstrate further the concept.

- Demonstrator at Kızıldere (western Türkiye, Fig. 3-b, Table 1), within the projects GECO [90] and SUCCEED [91]. The concentration of CO₂ can reach up to 4 % by weight depending on site characteristics [88]. Several solutions are under investigation: i. within the GECO project; a reinjection system was commissioned by the end of 2022, sized for 1700 t/y [92]; ii. within the SUCCEED project, an existing well will be used to inject CO₂ into the reservoir in a supercritical state [88].
- Within the GECO project: demonstrator initially planned at Castelnuovo (Italy), replaced by demonstrator at Hveragerði (Iceland) [93].
- Several other active NCG reinjection projects have been conducted in different locations [18]: in Umurlu, Türkiye, in 2017; in Ngatamariki, New Zealand, in 2021–2022; and in recent years in the Te Huka plant, New Zealand.

In addition to pilots and demonstrators, numerous modelling studies

have been carried out to tackle scientific and technical challenges [89, 94–98].

Critical perspective: These concepts hold great promise for integrating geothermal energy into the renewable, decarbonized energy mix in areas with high NCG. However, managing the additional costs and technical challenges is crucial to maintaining economic competitiveness of geothermal energy. Alongside continued demonstrations, key research is needed to understand gas flow dynamics and how geothermal extraction/reinjection impacts it.

2.3.2. Carbfix concept and variants

Description: The Carbfix concept stems from a CCS concept. The original idea targets dissolved CO₂ storage through injection into reactive rocks (such as mafic or ultramafic lithologies), provoking CO₂ mineralization and, thereby, permanently fixing carbon with a negligible risk of return to the atmosphere [99,100]. The concept was primarily developed in Iceland where the geological characteristics (basalts) are highly favourable. The Icelandic context is also favourable for high-temperature geothermal heat extraction and, since the extracted steam contains CO₂, the CO₂ required for concept demonstration was able to be sourced on-site, thus falling within the perimeter of this review, even if the concept can also be deployed with an external source of CO₂ for CCS purposes only.

A variation was announced in 2022 in New Zealand [101], consisting of capturing NCG naturally present in the geothermal fluid and to reinject them via the reinjection well. In order to enhance CO₂ mineralization in the absence of the favourable geological features, “the plan is to inject ions along with the reinjected gases that will cause them to petrify into common and non-toxic minerals – CO₂ into calcite, and H₂S into pyrite”.

These integrated geothermal-CCS operations, where CO₂ from geothermal fluid is reinjected at various depths in a dissolved form (either within the geothermal reservoir or at distinct depths) to achieve rapid CO₂ mineralization, might be considered as a special variant of “CO₂ reinjection concepts”, with the objective of rapid mineralization being the specific feature.

From concept to demonstration: The Carbfix concept (Fig. 3-c) has been widely investigated, as reflected by the high number of scientific papers (list available at: <https://carbfix.com/scientific-papers>). The first industrial demonstrator site in Hellisheidi started in 2012 and was then upscaled in 2014 to target a hotter and deeper reservoir [102,103]. The gases (CO₂ and H₂S) are captured directly from the geothermal power plant and dissolved in the condensed steam, then injected at a depth of ~800 m into the basaltic reservoir at temperatures of ~250 °C (Table 1). Over 50 % of the injected carbon is fixed as carbonate minerals within months after injection using this upscaled system. The second industrial demonstrator site, Nesjavellir [104], started injection in 2023 [105] and has similar geological features.

In September 2022, the New Zealand variation was announced. Limited information has been found regarding the current status of this demonstrator.

Critical perspective: The concept has already been demonstrated. However, further efforts are needed to prove the effectiveness of permanent storage through monitoring, measurements, and verification. The concept cannot be widely replicated onshore without the specific conditions found in Iceland, which are rare. The New Zealand project deserves attention to explore whether in situ mineralization can be further engineered.

2.3.3. CLEAG-AATG concept

Description: The information in this section is derived from the AATG company website [106] and personal communication. The concept, referred to as CLEAG (Clozed Loop Energy AG), was developed by AAT-Geothermae in Croatia, in 2013. This technology targets geothermal fluids containing methane and aims to harness the full energy potential of hot brines by exploiting both their heat (estimates:

100–120 °C at depths of 1800–2000 m; Table 1) and dissolved methane content. Methane is separated from the water and burned in a gas engine. Additionally, the concept involves the reinjection of: i. CO₂ naturally present in the produced geothermal fluid; ii. CO₂ from the exhaust gases of gas engines using methane originally contained in the geothermal fluid.

From Concept to Demonstration: this concept is not described in scientific literature, but a pilot is currently being deployed (see Fig. 3-d). The Draškovec geological formation has a methane content of about 0.2 % by weight. The demonstrator operations are scheduled to begin in 2025 (personal communication). To the best of available knowledge, the concept has not yet been demonstrated elsewhere.

Critical perspective: The concept is innovative, and the results from the upcoming demonstrator will determine whether the technical challenges can be effectively managed. Given the high heating value of CH₄ compared to hot water, the concept could be viewed as a hybrid between Enhanced Gas Recovery and geothermal energy production. This could raise acceptability and regulatory concerns that must not be overlooked. The occurrence of specific reservoir conditions (hot geothermal brine with a relatively high CH₄ content) raises the question of the reproducibility of the concept.

Table 2 provides a summary of the concepts introduced in 2.2.1, 2.2.2, and 2.3, highlighting their key distinguishing features.

2.4. Other synergies

2.4.1. Synergetic use through pressure management

Description: In this concept, both the CO₂ plume used for CCS and the geothermal brine mobilized during exploitation are located in the same geological formation (Table 1). These plumes are positioned at a sufficient distance to remain distinct based on their fluid footprints, yet they are close enough to influence each other’s pressure dynamics.

The CO₂ injected for CCS provokes a pressure increase in the reservoir. It limits injectivity and storage capacity and increases the risk of induced seismicity and leakage. Solutions of active CO₂ reservoir management (ACRM) have been proposed by different studies [107–111] to improve CCS performance. They consist of withdrawing water from the storage reservoir, possibly using this water for geothermal purposes (and reinjecting it at sufficient distance, at different depths, into the sea, etc.). This review focuses only on the options that operate hybridization between CCS and geothermal heat extraction. This solution is proposed in a limited number of articles. Pressure increase in the reservoir due to CO₂ injection could also facilitate geothermal brine pumping. Besides pressure management benefits, the synergy includes mutualization of the exploration phase and data sharing.

From Concept to Demonstration: There is a limited number of scientific articles dealing with this synergetic concept [110,112], and no pilot initiative.

Critical perspective: The concepts remain separate, ensuring technical feasibility, but require two viable projects locally, one for CO₂ storage and the other for geothermal energy. Cost sharing is limited, offering only marginal economic benefits, and handling non-reinjected water is another challenge. For these reasons, the concept is likely to remain a niche solution rather than scalable.

2.4.2. Synergetic dual use in the same reservoir

Description: Another possible synergy is to use the same reservoir for both geothermal heat mining and CCS (Table 1). The exploration phase, data acquisition, and some infrastructures can thus be mutualized. This concept was proposed by Tillner et al., in 2013 [113] with a case study in Germany as an illustration. In this concept paper, a production well was used for geothermal brine production. A unique injection well, located 7 km away, was used for both CO₂ injection and brine reinjection (with cycles), sharing the same wells for two different purposes.

From Concept to Demonstration: No other scientific article has

Table 2

Summary of main concepts introduced in section 2.2. The main features that distinguish these concepts are highlighted.

	Geothermal fluid characteristics	CO ₂ origin	Injection form	Trapping mechanism in the middle term	Philosophy
CO₂-Dissolved, BECCS	Low natural dissolved CO ₂ content	External source	Dissolved	Mainly solubility	Dual objective (geothermal and CCS)
CO₂-reinjection	Significant content of CO ₂ and other NCG	Geothermal fluid	Dissolved Liquid or Supercritical	Mainly solubility Mainly structural	Towards zero-emission geothermal power plant
Carbfix	Might contain NCG/CO ₂	Generally geothermal-fluid (or external origin)	Dissolved	Mainly mineral	CCS-driven concept originally, but can have a dual objective
CLEAG-AATG	Significant content of methane (and possibly NCG)	Geothermal fluid and methane combustion	Dissolved	Mainly solubility	Towards zero-emission geothermal power plant

been identified to push the concept forward since 2013.

Critical perspective: As with the previous concept, two distinct, viable projects are needed at the same location, with available CO₂ emissions and geothermal energy needs. Costs are somewhat more mutualized with shared infrastructure. However, it remains to be seen whether having a single well for both injections and alternating them is practically feasible.

2.4.3. Hybrid energy systems involving both technologies

Description: A complex hybrid approach was proposed by Buscheck and Upadhye in 2021 [111] to produce electricity with near-zero carbon emissions, or even negative emissions if biomass is used (Table 1). This approach integrates variable renewable energy, geothermal energy, and fossil energy with CCS into a single facility, significantly enhancing the efficiency of all energy sources. For example, geothermal energy pre-heats the fluid before combustion, achieving high temperatures with minimal fossil fuel use and high conversion efficiency. To optimize the CCS process, pure oxygen is used for combustion, resulting in high-purity CO₂. This CO₂ can be stored during periods of excess electricity. Geologically speaking, CO₂ injected in SC-CO₂ form is stored in a sedimentary formation. To manage pressure in the storage formations, brine is extracted at a distance, utilizing geothermal heat in the power plant. Some of the geothermal brine may be reinjected into a shallower formation. The shallower formation also serves for thermal storage.

From Concept to Demonstration: Only one conceptual scientific article has been found for this concept.

Critical perspective: Multi-energy technologies offer a promising pathway to achieve high energy efficiencies. While the system is complex and challenging to decipher, it may hold significant potential from an energy perspective. Further studies, followed by a pilot project, are necessary to fully evaluate its viability and benefits.

2.4.4. Geothermal energy used for capture

Variant 1: Davidson et al. [114] describe a concept where the primary objective is CCS (as presented in section 2.2.3). When analysing the whole chain, their work points out that the energy consumption of the CO₂ capture process is a non-negligible penalty for carbon reduction. If this energy comes from a non-carbon source, the environmental performance of CCS is improved. The work explores using geothermal energy to preheat the boiler feedwater. The study's theoretical results suggest that using geothermal energy at 150 °C could improve the performance of CCS. This concept focuses solely on integration through surface processes, without discussing geological settings. Only one conceptual scientific article has been found for this concept.

Variant 2: Another option proposed in the literature to use geothermal energy for capture consists of using geothermal energy in direct air carbon capture (DAC) [115–117]. This concept was not thoroughly investigated within the review, but constitutes a promising option of synergy between geothermal energy and CCS, as illustrated by the Orca [118] project in Iceland. In this project, the Climeworks direct air carbon capture system has been operated since 2021 with associated CO₂ storage (4000 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.

Critical perspective: These technologies are less complex from a subsurface perspective, as the coupling occurs only at the surface. Their implementation appears feasible, but it is essential to assess the advantages and limitations of geothermal energy within these systems compared with other energy solutions.

3. Are these technologies in competition?

This literature review reveals that some technologies share similarities, with certain ones emerging as specific cases of broader concepts. Not all can be deployed under the same geological conditions, and they occupy different roles in the CCS value chain, providing varied energy services such as electricity, heat, or energy storage. This section seeks to explore whether, for a given site and set of requirements, it is possible to identify the concepts most deserving of further investigation. In doing so, the research in this study demonstrates that, the level of competition within a specific configuration is low.

3.1. Regarding underground requirements

3.1.1. Technologies tailored for subsurface challenges

While many concepts focus on permeable porous aquifers (overlain by a caprock to ensure CO₂ confinement), several have been developed for specific geological conditions (Fig. 4).

For instance, reinjecting CO₂ naturally present in geothermal fluids has been devised to address the high CO₂ footprint of certain geothermal operations. The CLEAG-AATG concept addresses the particular geological characteristic of the gas content in geothermal fluids, which poses both an opportunity and a challenge: while the methane content provides an additional resource, the CO₂ produced by methane combustion must be captured and reinjected to achieve carbon-neutral energy production. In the Carbfix concept, unique geological conditions allow for the rapid mineralization of CO₂, ensuring permanent and secure storage. Concepts using SC-CO₂ as a geothermal vector adapt to fractured environments or depleted reservoirs, tailored to specific geological contexts without competing with other presented concepts. These geological features may either represent opportunities, such as the underground suitability for rapid mineralization, or constraints, like the presence of CO₂ in geothermal fluids.

3.1.2. Technologies targeting porous/permeable aquifers

Other concepts require similar geological features, such as a porous and permeable aquifer overlain by a caprock, with porosity ranging from 5 % to 25 % and permeability between around 10⁻¹⁵ and 10⁻¹³ m². The caprock is crucial to ensure CO₂ confinement.

The depth range may vary (Fig. 5), with an additional constraint for concepts involving SC-CO₂, which requires sufficient depth to maintain appropriate temperature and pressure conditions for the CO₂ to remain in its supercritical state (typically around 800 m). The targeted depth may also depend on the intended use for geothermal energy extraction.

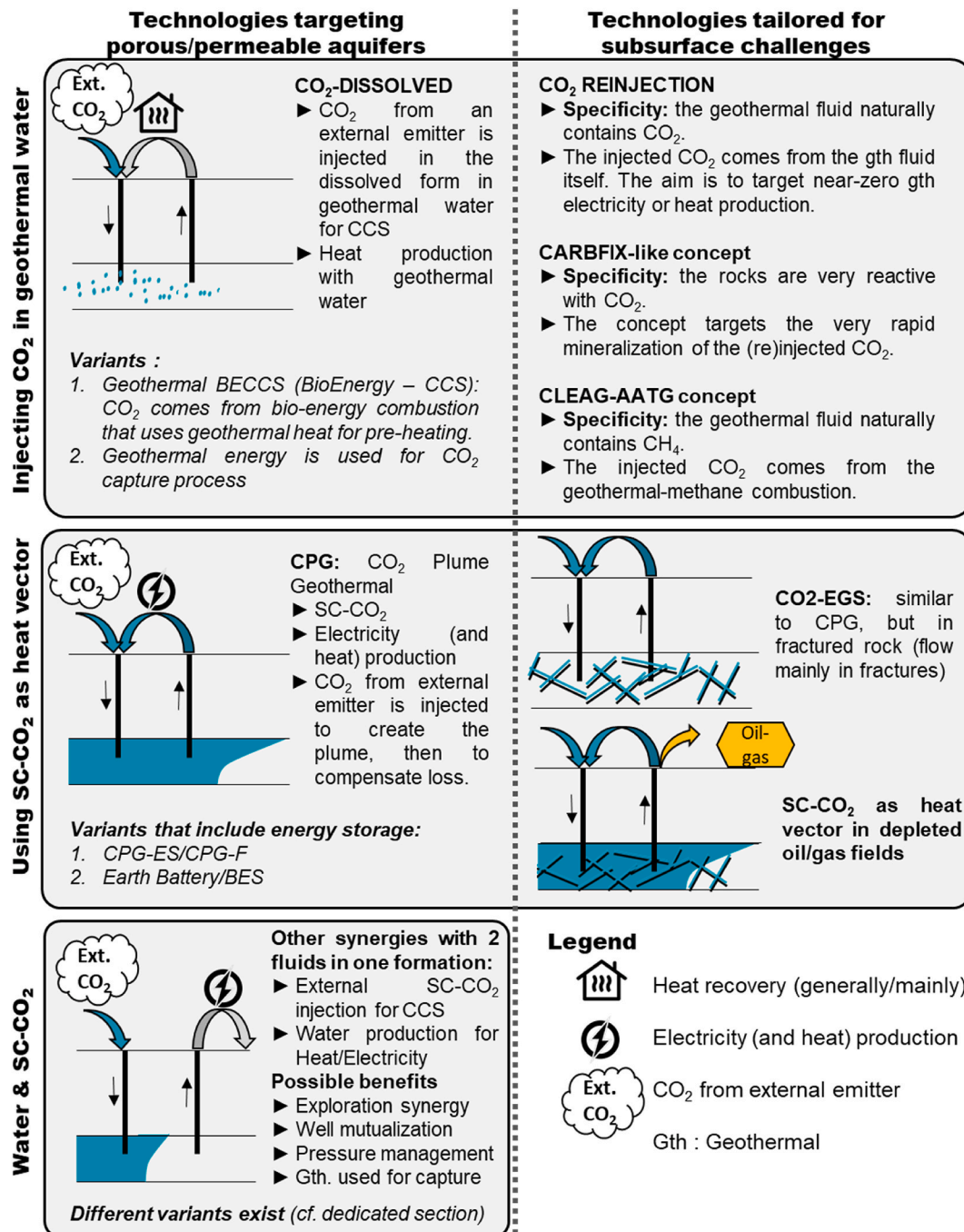


Fig. 4. Overview of simplified vertical cross-sections for key concepts discussed in this review, vertically classified by the initial categorization from section 2, and horizontally aligned according to underground requirements. On the left, concepts that necessitate relatively similar subsurface conditions (porous permeable aquifer overlain by a caprock), and on the right, concepts developed to accommodate specific subsurface characteristics. ‘Gth.’ represents geothermal energy extraction.

3.2. Considering a system-wide analysis

When considering subsurface conditions alone, a certain level of competitiveness between these concepts is observed. We propose to take this analysis further by integrating the entire value chain to refine these insights.

3.2.1. Fundamental differences regarding the CCS service

It is essential to consider the concepts holistically, rather than focusing solely on the subsurface dimension, to understand that the diversity of concepts represents a range of different solutions, each tailored to distinct stakeholders and addressing vastly different

specifications. Consequently, the level of competition between these various concepts is, in fact, quite limited.

When examining the upstream requirements of the technologies, particularly the scope of each concept and the stakeholders concerned, several distinctions can be made (Fig. 6).

- Group 1: Technologies designed for geothermal operators dealing with geothermal fluids rich in NCG. These concepts are not relevant for industries looking to store CO₂ emissions.
- Group 2: Integrated technologies that combine an energy production facility using an external fuel (e.g. biomass) with geothermal energy, optimizing performance through synergies between geothermal and

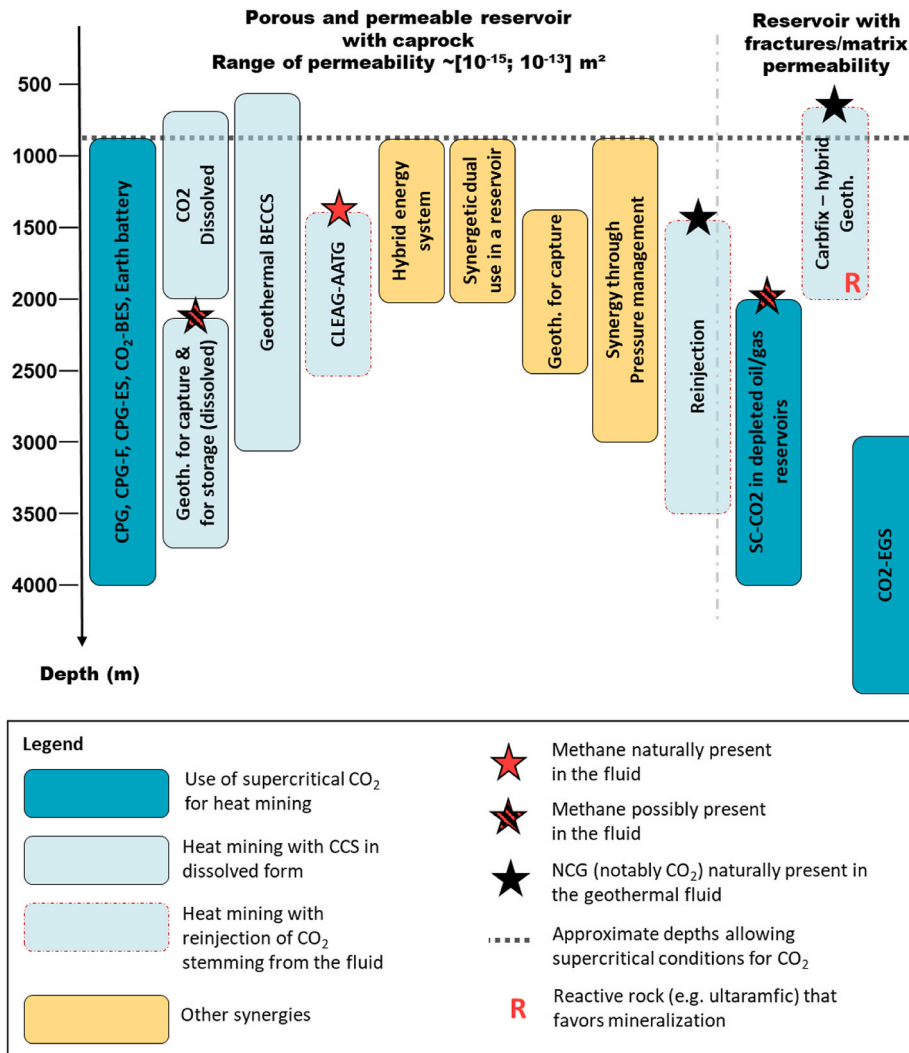


Fig. 5. Overview of concepts according to underground characteristics. Horizontally, the elements within each category are listed without any particular order of significance.

another fuel. These systems capture the emitted CO₂ and reinject it, either into the geothermal fluid or separately. Such integrated projects cover the entire value chain and do not offer CO₂ storage services to external emitters.

- Group 3: Technologies that provide CO₂ storage solutions for emitters of varying sizes, while also offering geothermal heat that can be used elsewhere. For example, the CO₂-Dissolved concept is suitable for small industrial CO₂ emitters (approximately <150 000 tons/year), whereas most other technologies are better suited to larger CO₂ emitters, so responding to different needs.
- Group 4: Technologies specifically aimed at CO₂ capture operators, which leverage geothermal energy to enhance the environmental and energy efficiency of the capture process.

Considering the CCS service provided by the technologies, in addition to the underground requirements, the cases of concepts actually being in some form of competition is very limited.

3.2.2. Differences regarding energy services

From a geothermal perspective, there are also differences in the services provided. In groups 2 and 4 (Fig. 6), the use of geothermal heat is already designated for internal uses within the concept, whether for a hybrid energy plant or to meet the energy needs of CO₂ capture.

In groups 1 and 3 (Fig. 6), the use of geothermal heat is not

predefined, but the targeted temperature range limits its application to thermal uses in some cases, while others aim for temperatures high enough to generate electricity. Additionally, some concepts offer an added service of energy storage (CPG-F/CPG-ES, earth battery, hybrid energy system) to help balance supply and demand.

The balance between geothermal and CCS services varies significantly across different concepts (Fig. 7). Some are primarily geothermal solutions with an optional CCS plugin, while others prioritize CCS with geothermal as a secondary feature.

When considering subsurface characteristics, the integration of CCS within the concept, the range of energy services offered, and the target stakeholders, it becomes apparent that these concepts are unlikely to compete directly in a project-specific context.

4. Path to commerciality and challenges

In assessing the needs of a specific site, it becomes apparent that direct competition among concepts is limited. However, it is unlikely that all concepts will follow the same developmental trajectories: some may successfully enter the market, while others may not. To advance along the technology readiness level (TRL) scale, these concepts require support from industry, with or without the backing of co-funded research projects, and in some cases, adjustments to regulatory frameworks are necessary. Potential competition for limited research funding

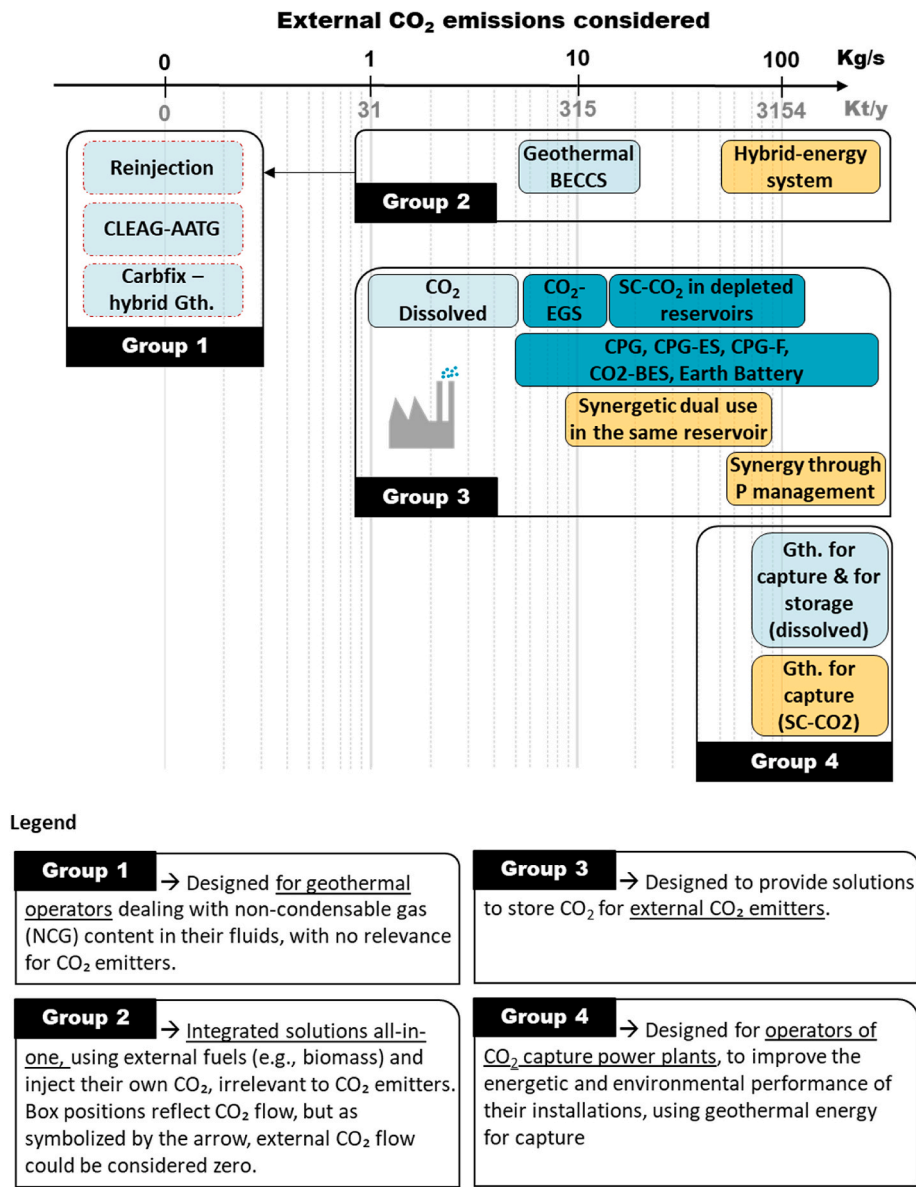


Fig. 6. Concepts categorization considering the different groups of stakeholders, and the level of CO₂ flows. Vertically, the elements are arranged without any specific order of significance, simply for layout purposes.

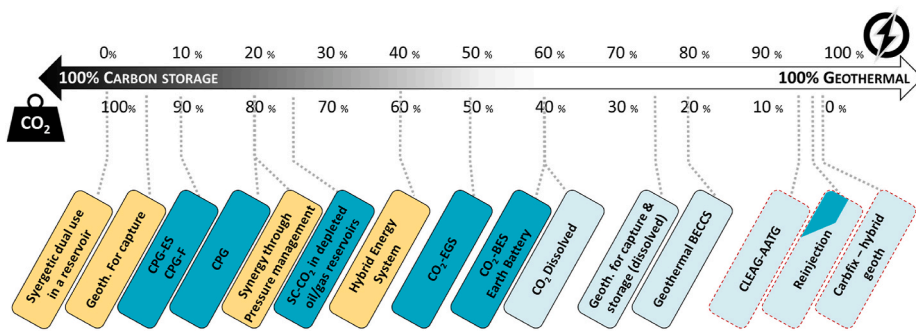


Fig. 7. Overview of concepts according to the focus on CCS and geothermal exploitation, using the index of services ratio defined in Ref. [19] (left: concepts close to CCS, right: concepts close to geothermal).

can be identified. When evaluating their performance across techno-economic, energy, environmental, and scalability dimensions, certain technologies are likely to emerge as leaders, while others might remain

sidelined. Although it is challenging to make definitive predictions at this stage, this section offers insights into the progression of these concepts and their journey toward commercial viability.

4.1. Different stages of development

The TRL scale is inappropriate here for the following reasons: i. Many concepts are presented from a theoretical perspective and correspond to low TRLs (1–4), making proper distinction and comparison difficult; ii. These concepts often involve a combination of sub-technologies with widely varying TRLs; iii. Varying scopes of the concepts reviewed would lead to biased comparisons —some focus solely on subsurface technology, while others encompass the entire system.

The most advanced concepts can be synthesized as follows (Fig. 8).

- The Carbfix concept has been tested since 2014 at industrial scale and has been the subject of extensive academic research, with encouraging results. It has been pushed within a CCS framework. The hybridization involving CO₂ sourced from geothermal processes corresponds to a pragmatic approach rather than a hybridization objective, which has likely acted as a facilitating factor.
- Reinjection is actively pursued within geothermal energy to align with the carbon neutrality goals of renewable energies, with emphasis on near-zero emissions and not on hybridization of geothermal energy and CCS. In this category, the CLEAG-AATG concept stands out as being advanced operationally despite no published scientific research.
- Among the concepts that fully embrace hybrid characteristics, the two progressing towards short-term demonstration, based on the available information, are the CPG concept, which involves an active

European industrial consortium, and the CO₂-Dissolved concept, with an active French academic-industrial consortium. Both aim to deploy a demonstrator within the coming years.

4.2. Scientific, technical, and operational challenges

4.2.1. Why such challenges?

A common characteristic of all concepts involving subsurface activities is the high level of uncertainty, due to the natural variability of subsurface properties and challenges in the acquisition of data. These uncertainties generally lay the groundwork for substantial complexity. The scientific challenges are particularly pronounced when it comes to understanding thermo-hydro-mechanical and microbial-geochemical phenomena in systems involving multiple fluids (e.g. brine, CO₂, potentially methane and other NCG). These challenges are further complicated by the need to account for varying phases (vapour/gas, liquid, supercritical), evolving properties influenced by pressure, temperature, and composition, as well as fluid-rock interactions, including dissolution and precipitation processes. Significant progress has already been made on brine-CO₂ systems within the CCS field but much work still lies ahead. These technical challenges are present for all the concepts discussed in this review, although their ability to manage or handle complexity varies based on factors such as CO₂ state, depth, geological features, and the extent of prior work.

For some concepts, there is an additional high level of engineered underground technical complexity, including deep wells, multiple wells,

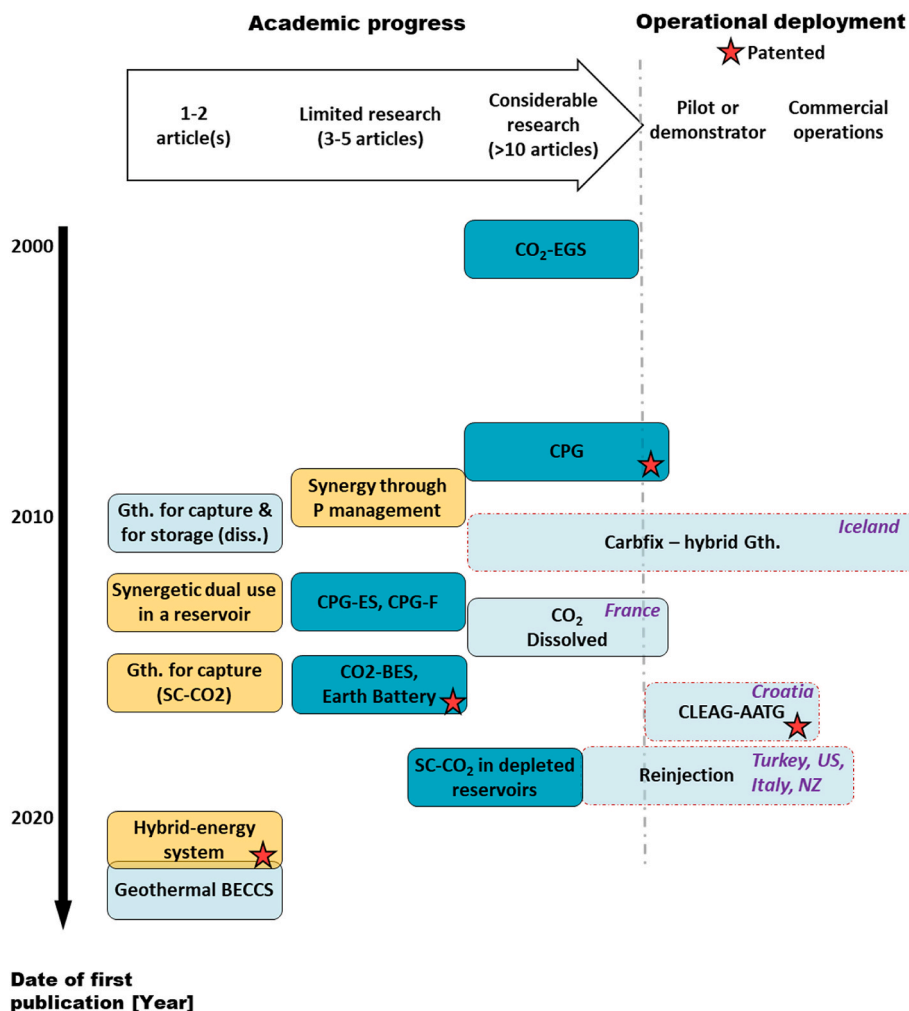


Fig. 8. Progression from academic research to commercial viability. The vertical axis indicates the first year the concept has been proposed in publicly available articles/websites.

multi-lateral wells, stimulations, surface installations, and the need for several aquifers at different depths. Examples include CO₂-EGS, CPG-ES/CPG-F, and earth battery systems. Alternatively, systems like BECCS and Hybrid energy systems exhibit high complexity due to their numerous integrated components.

Integrating the entire chain presents challenges, particularly in securing a local CO₂ source or establishing a CO₂ transport infrastructure that delivers the required quantities to the target site, as well as connecting to energy consumers. The flow rates in some concepts are such that they may seem difficult to implement in practice, even though they are convincing from a theoretical standpoint (e.g. earth battery, CCS-driven concept).

4.2.2. Deploy rigorous risk management plans and guarantee CO₂ confinement

To achieve a synergy between geothermal energy and CCS, it is essential that the regulatory conditions for CCS are fully met. One of the main objectives of CCS regulations is to ensure the CO₂ will remain confined within the intended reservoir for a long period of time. The most advanced CCS regulations include the CCS directive in Europe ("Directive 2009/31/EC"), and the class VI wells in the United States, as regulated by the Environmental Protection Agency. More generally, the requirements for CO₂ long-term containment are described in the ISO standard relevant to geological storage of CO₂: ISO 27914:2017. Numerous frameworks have been developed within the CCS field to ensure rigorous risk management practices (e.g. Ref. [119]). For almost all concepts, limited information has been published regarding risk management (except for concepts inspired by CCS), despite the significant number of academic articles for some of the concepts (e.g. CPG, CO₂-EGS). Compared with theoretical computations, operational scenarios might require adjustment to align with risk management protocols.

Among the various challenges that must be addressed, the long-term containment of CO₂ is paramount. The integrity of caprock and wells represents major concerns. CO₂ containment is especially critical for concepts relying on the use of SC-CO₂. Hybrid concepts require drilling the caprock with additional wells, which increases the risk. Using CO₂ as heat vector, rather than injecting it only once, could also significantly increase the risk of leakage. For depleted oil/gas reservoirs, a potential concern would be the integrity of abandoned and legacy wells, which could serve as pathways for CO₂ leakage out of the natural oil/gas reservoir.

To move towards the demonstration of these concepts, it is crucial to demonstrate rigorous risk management for the permitting process, for the secure execution of the project and for societal acceptance. This step is not a major leap, as it can build upon the work already done for CCS and be adapted to the specificities of concepts that combine geothermal energy with CCS synergies.

4.2.3. Maintain performance over time

The challenges faced in any geothermal operation are also applicable to concepts involving synergies. Thermal breakthrough occurs when cooler fluid, usually from injection wells, reaches the production wells more quickly than expected, leading to a noticeable drop in the temperature of the extracted geothermal fluid, thereby reducing the efficiency of the geothermal system. This phenomenon typically happens when the injected fluid follows preferential pathways in the subsurface, such as fractures or high-permeability zones, bypassing the hot rock mass intended to heat it. Thermal breakthrough can occur even earlier with SC-CO₂ due to its higher mobility.

Similarly, concepts like CO₂-Dissolved can encounter a risk of "CO₂ breakthrough": if the dissolved CO₂ reaches the production well, the solubility limit may prevent further injection of the initially planned quantities, thereby reducing progressively the performance of the CCS component of the operation.

Therefore, when implementing a concept that achieves synergy, it is

crucial to have a thorough understanding of the reservoir in advance, reduce various uncertainties, implement effective monitoring and develop predictive models as reliably as possible to effectively design well placement and the operational scenario.

4.2.4. Manage water quality issues

Water quality issues are critical in geothermal operations, and neglecting them can increase certain risks or degrade the performance of the system over time. The primary risks include: clogging or dissolution in the near-well (which can affect injectivity, productivity or stability), scaling and corrosion in both wells and surface installations. These issues are common in geothermal operations, primarily due to pressure and temperature changes.

In most of the concepts discussed here, beyond the temperature changes induced by the geothermal aspect, CO₂ is present either in dissolved form or as SC-CO₂. Chemically speaking, SC-CO₂ does not yield ionic dissolution products, which can mitigate the mineral dissolution/precipitation challenge in the absence of water. However, practical field conditions may offset these theoretical advantages, especially due to the presence of residual water. In its dissolved form, CO₂ lowers the pH, which can be beneficial in counteracting temperature-induced precipitation but may also intensify certain chemical reactions. In concepts that also involve methane or oil residues, water quality issues become even more pronounced. Microbiological phenomena, depending on the reservoir, pressure-temperature conditions, and the fluid involved, likely deserve attention as well, though they remain under-investigated and not well understood.

Finally, it may also be necessary to consider risks to shallower aquifers, particularly the risk of interconnection between aquifers. However, these risks are already commonly addressed in both CCS and geothermal operations, so applying best practices should be sufficient.

4.2.5. Manage seismicity

Underground operations inherently alter the characteristics of a reservoir by injecting or extracting hot and/or cold fluids, leading to stress changes that can cause micro-seismic events. Other factors, such as disturbances from drilling or stress redistribution due to variations in fluid volume within the reservoir, can also trigger induced seismic events.

For CO₂-EGS and CPG concepts, using CO₂ as the heat transfer medium instead of brine is expected to mitigate overpressure, given the high compressibility and expansivity of SC-CO₂. This could make mechanical effects, particularly induced seismicity, more manageable. However, this remains theoretical and speculative and requires empirical confirmation.

For concepts involving dissolved CO₂, induced seismicity does not appear to pose significant additional challenges compared to conventional geothermal operations.

Given that induced seismicity is highly site-specific, this aspect must be carefully evaluated and, if necessary, studied in detail for each project.

4.2.6. Addressing additional specific challenges

In addressing scientific, technical, and operational challenges, some concepts present more specific issues. The most significant of these are outlined in this section, though this list is not exhaustive.

CPG, CPG-ES, CPG-F, earth Battery: For concepts that rely on exploiting a CO₂ plume, the system is initiated by injecting CO₂ over several months or years. Once the SC-CO₂ plume covers both the injection and production wells, geothermal exploitation begins. A major practical challenge is managing the variable CO₂ flow requirements between the initialization phase and normal operations. Besides, maintaining the purity of CO₂ for geothermal fluid production is dependent on numerous factors and can be difficult to achieve and sustain over the operational lifespan.

Synergetic use through pressure management, Hybrid energy

systems: Concepts that propose pressure management solutions to avoid excessive overpressure appear theoretically attractive. However, the management of the produced water represents a challenge. The water's quality, especially its salinity will affect the environmental impact of its disposal. Options include discharge into seawater or a nearby river, or into other aquifers.

4.3. Economic, societal, regulation challenges

4.3.1. Economic challenges

As outlined in Sections 2 and 4.1, the current TRL of the majority of these concepts is too low to allow for meaningful economic analyses. While there have been attempts to assess the economics of several of these concepts—efforts that are commendable and help advance them toward pre-feasibility—it is not particularly useful to compare figures of these early-stage studies. Instead, a qualitative discussion is provided in this section.

As mentioned in the introduction, economic synergy was a key motivation behind the development of most concepts introduced in this review. However, these technologies can also bring increased complexity, higher associated costs, and greater risks for the project. Another highly uncertain factor is the revenue from CO₂ storage. Despite the establishment of a carbon market, this revenue stream has been slow to develop, offering limited economic incentive for storage projects so far.

For concepts that reinject their own NCGs (group 1, Fig. 6), the paradigm is somewhat different. Rather than pursuing a second revenue stream, these concepts focus on avoiding penalties related to emissions. The primary revenue is derived from the sale of decarbonized renewable energy (with the exception of CLEAG-AATG, which also valorizes methane). In certain local contexts, attractive feed-in tariffs for renewable energy may be offered, provided the energy is proven to be carbon-free. Therefore, the challenge is to minimize the additional costs of reinjection so that the price of geothermal energy can remain competitive with other renewable sources.

For concepts gathered in group 3 (Fig. 6), which offer external CCS storage and geothermal energy supplies.

- **SC-CO₂ concepts** involve high investment costs, and the development risks place future revenue streams at significant risk. The supply of CO₂, given the large quantities required (more particularly in the initialization period), also poses a challenge and could be more of an economic burden than an additional revenue stream for initial demonstrators.
- **Concepts with synergetic use of the same reservoir** benefit from the fact that the two operations can remain relatively independent. However, the cost-sharing between the two operations is also only partial, and the economic gain from synergy is limited.
- **Concepts using dissolved CO₂** face relatively high investment and operational costs per mass of stored CO₂. To be economically viable, the concept should be as scalable and modular as possible, with a “plug & play” approach to facilitate integration.

Systemic “all-in-one” concepts (group 2, Fig. 6) and concepts focusing on CO₂ capture (group 4, Fig. 6) require feasibility studies, which are somewhat simpler to evaluate economically since they do not require a CO₂ supplier.

4.3.2. Political and societal dimension

As with all first-of-a-kind projects, particularly those involving subsurface operations like the concepts discussed in this study, potential societal barriers must be recognized as significant factors that could impact negatively the feasibility of the project.

The hybrid nature of concepts combining geothermal energy and CCS, and how this might affect perception compared to single-purpose technologies, has not yet been studied to the best of available

knowledge. Defenders speculate that CO₂ plume geothermal (CPG) systems could improve public acceptance of CCS operations by framing CO₂ not just as a waste product requiring permanent storage but as a working fluid that can extract geothermal energy [120]. However, this hypothesis requires empirical validation.

Given the low TRL of these concepts and the evolving landscape for energy and climate change mitigation solutions like CCS, it is premature to draw conclusions about their economic, political or societal dimensions.

4.3.3. Regulations

The regulatory framework may present challenges for implementing synergetic concepts such as those combining geothermal energy with CCS. As regulations are highly specific to each country, the review provides only high-level considerations.

Hybrid concepts are likely to fall under two different regulatory frameworks, complicating the permitting process and making it potentially cumbersome and tricky. In some cases, under current regulations, certain concepts might not be authorized. For instance, CCS permits and associated CO₂ storage credits are sometimes contingent upon assurances that the CO₂ will not be back-produced (e.g. “U.S. Code § 45Q - Credit for carbon oxide sequestration [121]).

However, these regulatory challenges are not insurmountable. As new technologies emerge, regulations are expected to evolve accordingly. In Europe, for example, the net-zero industry act (NZIA), officially adopted by the European Union and coming into force in June 2024 [122], specifically addresses the need to reduce administrative burdens and streamline permit-granting processes to improve conditions for investment in net-zero technologies, including geothermal energy and CCS. The Act introduces provisions to simplify permitting procedures, which are frequently cited as significant obstacles to the timely deployment of clean energy projects. This regulation could theoretically facilitate the establishment of new pilot projects across Europe.

4.4. Potential estimates

At this stage, predicting the techno-socio-economic viability of the various concepts remains challenging. Significant efforts are still required to achieve a TRL level that allows for accurate assessments. To prioritize certain concepts, one key consideration is their global potential, considering both energy supply and CO₂ storage contributions.

The overall potential of a concept depends on the impact of individual plants (Fig. 1) and their replicability. A small-scale concept can have a high global potential if it is easily replicable, whilst a concept with significant individual contributions might offer limited overall potential if only a few “champions” can be deployed.

To precisely assess replicability, detailed mapping analyses are necessary, taking into account underground geology and geothermal potential as well as surface features such as the location of CO₂ emitters and local heat demand. Preliminary efforts have been made in Ref. [19], but a comprehensive estimation of each concept's potential, considering their specific characteristics, is currently unfeasible due to the varied advancement stages of each concept. While some studies discuss replicability, differing methodologies and assumptions hinder direct comparison.

For concepts dependent on specific geological contexts, global potential is linked to the prevalence of the associated conditions worldwide.

- **CO₂ reinjection concepts:** These are critical in regions with significant geothermal potential, e.g. in Türkiye, New Zealand and Italy, where they are essential for decarbonized geothermal energy. Developing the necessary technologies for high-CO₂ contexts could also enable their application in lower-CO₂ settings, which, though less critical now, will become increasingly important on the path towards carbon neutrality. Methane separation and valorization in

decarbonized systems is another promising avenue, applicable in various geological contexts, though precise potential estimates are currently unavailable.

- **Carbfix context:** Onshore deployment is limited to specific geological settings. Offshore, the potential is significant for the CCS component with external CO₂ inputs, but this diverges from the geothermal-CCS synergy.
- **Depleted oil/gas end-of-life valorization:** The theoretical potential is high given the global distribution of oil and gas operations. CO₂ utilization has proven effective in this field, but the geothermal potential from CO₂ remains to be fully assessed, considering also surface heat demand, economic and regulatory factors.
- **EGS concepts:** The main challenge to large-scale enhanced geothermal systems (EGS) deployment is the lack of techno-economic proof rather than geological factors. Although suitable geological volumes could be vast with perfected techniques, EGS growth has been limited, especially outside specific favourable areas. The use of SC-CO₂ adds complexity, limiting its application to regions where effective and secure CO₂ storage can be demonstrated.

For concepts targeting porous and permeable aquifers capped by impermeable rock, numerous potential assessments have been conducted over recent decades, in the field of CCS and geothermal energy. Significant underground formations are known to meet the required criteria. To evaluate the potential of various concepts, it is essential to consider not only the geological suitability but also the ease of replication. Among CO₂ storage concepts for external emitters, technologies vary in scale—from large-scale concepts like the earth battery, to CPG and its variants, and finally, CO₂-Dissolved concepts. While finding suitable conditions for CO₂-Dissolved is simpler than for the earth battery, its individual contribution is much smaller. The economic viability of CO₂-Dissolved hinges on optimizing the cost of capture and injection, as the volumes stored per site are limited. A key challenge is developing a technology that is easy to deploy, allowing for a “copy-paste” approach with minimal site-specific studies. Conversely, systems using SC-CO₂ can justify higher initial investments due to the larger volumes involved. At this stage, it is difficult to compare the global potential of each concept or determine whether these hybrid approaches will compete effectively with single-purpose geothermal or CCS concepts.

5. Conclusion and recommendations

Even though it is important to keep in mind that certain aspects may have been inadvertently overlooked, this study offers a comprehensive overview of hybrid concepts that integrate CCS with geothermal energy production, identifying and classifying 15 distinct concepts. Three main categories emerged: i. SC-CO₂ as a heat vector, ii. water-driven geothermal concepts with CO₂ (re)-injection either for CCS purpose or for geothermal production with near-zero emissions, and iii. Lighter synergetic uses.

At best, these concepts are currently at the stage of early pilots or first demonstrators. Significant scientific, technical, and operational challenges must still be addressed to advance them to higher TRL levels and to provide tangible data for economic, societal, and replicability comparisons.

This research has taken a step back to analyze the various concepts from different perspectives, aiming to assess the extent to which they compete with one another. By relying on a series of infographics that provide a synthetic overview, the research demonstrates that for a specific site with defined project requirements, the number of technologies to consider is quite limited, with virtually no competition among them. Instead, competition exists at a broader level. Given the significant efforts required to advance a technology to commercial deployment, it is likely that those with the highest overall potential—considering both individual capabilities and replicability—will be promoted by industry stakeholders, co-funded research

projects, or other support mechanisms, ultimately coming to fruition. At the time of the review, many concepts are either emerging or progressing toward pilot-scale implementation. It is difficult to make predictions about the future of these technologies. Consequently, the results presented in this work provide a provisional perspective that will soon require an update. Future iterations should incorporate more refined insights into the scale of technical challenges, techno-economic analyses, assessments of potential, and life cycle analyses.

This review aims to offer both the scientific community and policymakers a comprehensive overview of the various concepts, emphasizing the potential critical role of hybrid geothermal-CCS systems in meeting decarbonization goals within the pressing timelines imposed by the climate crisis. To progress, it is essential to encourage the development of demonstration projects and foster collaborative research initiatives to tackle scientific and technical hurdles. Economically, there must be real incentives for CO₂ storage or emissions reduction, alongside a more flexible regulatory framework to accommodate hybrid applications. Additionally, it is crucial to continue supporting societal changes necessary for these promising technologies to be discussed and debated within a society that is aware of and engaged in the challenges at hand.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Chat GPT in order to improve language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Annick Loschetter reports financial support was provided by International Energy Agency Greenhouse Gas Research and Development Programme. BRGM (and C. Kervevan as a main contributor) is one of the main actor for the CO₂-Dissolved concept, presented in this review. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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