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Perspective

The promise of coupling geologic CO_2 storage with sedimentary basin geothermal power generation

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SUMMARY

Achieving ambitious greenhouse gas mitigation targets will require technological advances and cost reductions in dispatchable carbon-free power generation sources that can provide load following flexibility to integrate high penetrations of variable wind and solar power. Several other sectors may be difficult to decarbonize and a net-zero or net-negative carbon economy may require the deployment of geologic carbon dioxide (CO_2) storage. Utilizing CO_2 as a working fluid for geothermal energy production and energy storage can achieve both goals: isolating CO_2 from the atmosphere and providing valuable power system services to enable high penetrations of variable carbon-free electricity production. The use of CO_2 as a working fluid facilitates access to low-grade heat in sedimentary basins, which are widely available and could allow for strategic citing near CO_2 sources or where power system flexibility is needed. In this perspective piece, we summarize the state of knowledge for sedimentary basin CO_2-geothermal, sometimes referred to as CO_2 plume geothermal, and explore how it could support decarbonization of the energy sector. We also present the potential for using geologically stored CO_2 for bulk energy storage which could provide valuable time-shifting and other services to the power grid. We explore the promise and challenges of these technologies, identify key research gaps, and offer a critical appraisal of the role that policy for a technology at the intersection of renewable energy, energy storage, and geologic CO_2 storage may play in achieving broad deployment.

THERE IS A NEED FOR DISPATCHABLE CARBON-FREE POWER AND GEOLOGIC CO_2 STORAGE TO ACHIEVE DEEP DECARBONIZATION

Anthropogenic emissions of greenhouse gases—most notably CO_2—are accelerating global climate change (IPCC et al., 2021). The negative environmental, economic, and social effects of climate change have motivated substantial efforts to decarbonize economies. Many pathways to achieve deep reductions in greenhouse gas emissions require the power sector to drastically reduce CO_2 emissions while simultaneously electrifying other sectors, such as transportation and heating (Krey et al., 2014; Williams et al., 2012; National Academies of Science, Engineering and Medicine, 2021; Jenkins et al., 2018). Decarbonization of the power sector can occur through a transition to less carbon-intensive fuels (e.g., from coal to natural gas), the displacement of fossil fuels (e.g., from coal to nuclear), the rapid increase in deployment and utilization of renewable energy (e.g., more use of wind, solar, and geothermal), and broad implementation of geologic CO_2 storage (GCS).

Although wind and solar power have become increasingly cost effective, (U.S. DOE EIA, 2021) high penetrations of variable wind and solar energy capacity can pose grid integration challenges and result in the curtailment of these carbon-free generation sources and diminishing reductions in net CO_2 emissions (Denholm et al., 2015; Arbabzadeh et al., 2019; Das et al., 2020). Figure 1 illustrates these challenges, with multi-day periods of high wind generation followed by periods of low wind output (Southwest Power Pool), and diurnal patterns of solar generation balanced by increasing imports and natural gas generation during the off-peak hours (California Independent System Operator). In both regions, there are time intervals where carbon-free generation exceeds 75% of total generation, and other periods where this share drops to 20%. The challenges posed by integrating variable wind and solar can be addressed with the

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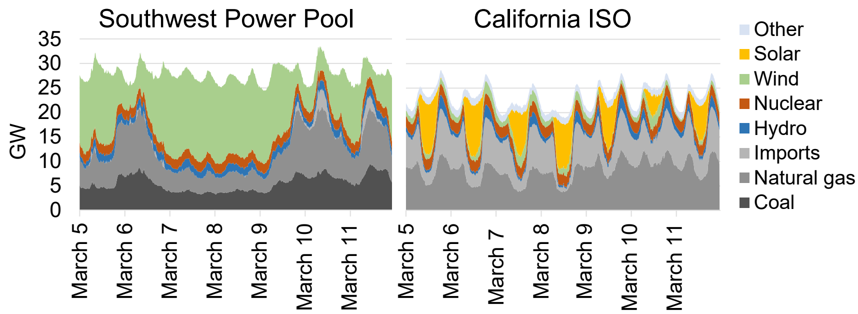

Figure 1. Generation mix for one week of March 2020 in two regions of the United States, showcasing the need for flexible, dispatchable carbon-free generation sources

The Southwest Power Pool is a wind-rich area that spans the central farmlands, and the California Independent System Operator serves much of the most populated US state and leads in solar-generated electricity.

addition of energy storage, expanded transmission capacity, and increased grid flexibility (Jenkins et al., 2018; Braff et al., 2016).

The addition of *flexible* carbon-free generation sources could enable deeper levels of decarbonization on grids that are challenged by high penetrations of wind and solar capacity. (Sepulveda et al., 2018) These flexible sources could include load-following renewables to balance generation variability, as well as short- and long-duration energy storage that can accommodate wind and solar generation that would otherwise be curtailed and provide power during extended periods of low wind and solar output. Beyond the power sector, several other major sources of emissions, such as cement and steel manufacturing, may be difficult to decarbonize and a net-zero carbon economy may be cost-effectively achieved with deployment of GCS (Davis et al., 2018). Although economic challenges remain in scaling up GCS, coupling GCS with flexible geothermal electricity production and energy storage could serve both goals of providing grid flexibility and isolating CO_2 from the atmosphere.

SEDIMENTARY BASIN CO_2-ENABLED GEOTHERMAL UTILIZATION: THE STATE OF THE TECHNOLOGY

Deep saline aquifers in sedimentary basins have been widely investigated for GCS – which is an essential element of almost all least-cost pathways for decarbonization (Jenkins et al., 2018). This permanent isolation of CO_2 from the atmosphere at depths greater than 800 m below the surface is also a crucial component of the major "negative emissions" technologies that extract CO_2 directly from the atmosphere (i.e., direct air CO_2 capture and bioenergy CO_2 capture and storage). At present, there are 65 geologic CO_2 storage projects worldwide, of which 26 are operating, and 40 $MtCO_2$/yr are being stored.[13] (Global CCS Institute, 2020).

If the CO_2 is emplaced in an aquifer within a sedimentary basin geothermal resource, it may be possible to circulate a portion of the geologically stored CO_2 in a closed system between the subsurface and the surface to produce thermal energy. The goal of GCS is to store the CO_2 in the subsurface to isolate it from the atmosphere, but the CO_2 does not necessarily need to always be in the GCS reservoir. The geologically stored CO_2 could be used as the geothermal heat extraction fluid and the heat could be used directly or converted to electricity in a geothermal power plant, before reinjecting the CO_2 into the subsurface. In this way, a CO_2-driven geothermal power plant may be added to a GCS site, or prospective site assessment could consider the utility for both CO_2 storage and geothermal heat extraction.

The use of CO_2 for geothermal heat extraction was originally proposed for geothermal systems that were hot but did not contain water (steam) or did not have sufficient permeability to sustain water-based heat extraction (Brown, 2000). With the enormous heat resource in deep hot dry rocks (HDR), where the geothermal temperature gradient can be 60°C/km or greater, the idea was to create an enhanced geothermal system (EGS) to tap extremely low intrinsic permeability by artificial stimulation techniques – much like hydraulic fracturing for unconventional oil and gas production from tight shale reservoirs (Tester et al., 2006). Such stimulation can engender concerns about triggering earthquakes and limit deployment

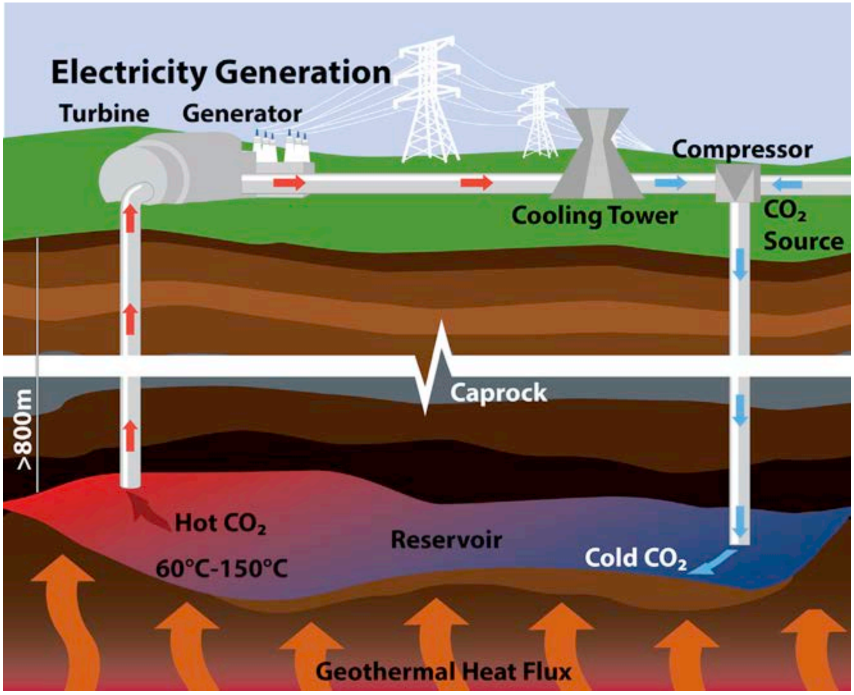

Figure 2. Sedimentary basin CO_2-enabled geothermal utilization system

(Breede et al., 2013; Schultz et al., 2020; Majer et al., 2007). In contrast, the deep aquifers in sedimentary basins that are targeted for GCS are naturally porous and permeable, which may facilitate sufficient fluid flowrates and capacities. These basins do not require the level of stimulation that HDR systems for EGS need, and are relatively ubiquitous worldwide (IPCC et al., 2005).

Sedimentary basin geothermal resources typically have lower temperatures (60–150°C) than potential HDR resources or the dominant, albeit limited, resources used for existing geothermal power development—hydrothermal settings with faulted and fractured systems with high heat flow and natural or artificial fluid recharge. In part due to the lower temperatures, sedimentary basin geothermal resources have not been studied as much as HDR or conventional hydrothermal resources (U.S. DOE, 2019). Available resource estimates for the contiguous United States alone are enormous; the median estimate is 800 million TWh for depths shallower than 3 km[20](U.S. DOE, 2019), which is several orders of magnitude larger than the US energy system. Because US basins may be representative of basins worldwide (Deng et al., 2017), the resource base is unlikely to be a limiting factor.

In the aquifers in these basins that are to be used for CO_2 storage, the temperatures and pressures are above the critical point of CO_2 (31.1°C, 7.4 MPa), which causes the CO_2 to be in a supercritical phase (i.e., having the density of a liquid and the viscosity of a gas). Compared to the native brine, CO_2 has a higher mobility at reservoir conditions, which more than compensates for its lower specific heat if it were to be used as a working fluid for heat extraction. Further, the density of CO_2 is highly temperature-dependent and, despite Joule-Thomson cooling as the CO_2 ascends in the production well (Pan et al., 2015), a self-convecting thermosiphon can develop between the cool (more dense) CO_2 in the injection well and the hot (less dense) CO_2 in the production well (Atrens et al., 2009; Adams et al., 2014). Although not necessary for CO_2-driven geothermal heat extraction (Adams et al., 2021a), this thermosiphon can provide a meaningful contribution to flow rates, heat extraction, and electricity generation (Adams et al., 2014; Atrens et al., 2010) if some considerations (e.g., thermally insulated wells) are addressed (Pan et al., 2018).

As illustrated in Figure 2, the hot CO_2 that is produced from the reservoir can be used to generate electricity. This hot CO_2 can be expanded in a turbine to generate electricity (direct system) or its heat

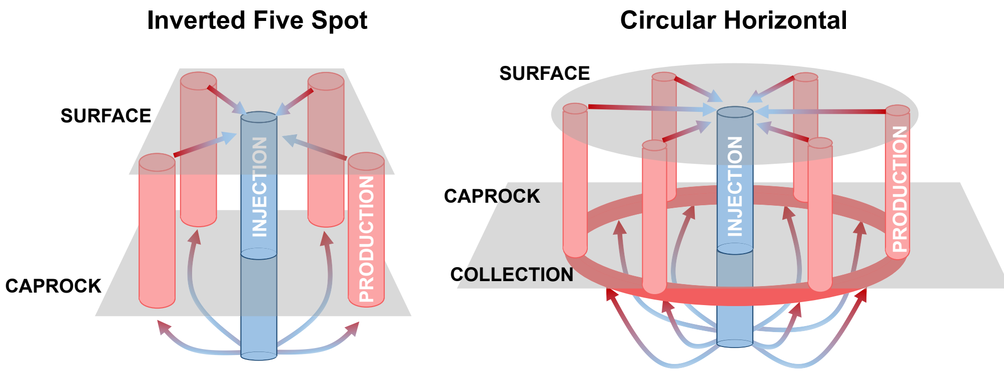

Figure 3. Two well pattern options for CO_2-enabled geothermal utilization: inverted five-spot and circular horizontal

transferred to a secondary fluid such as R254fa or CO_2 (indirect system). (Adams et al., 2015) This work, which couples power cycle, wellbore, and reservoir models, has shown the advantage of CO_2 over brine as the geothermal heat extraction fluid decreases with deeper reservoirs; CO_2 is preferred in 1 km deep reservoirs whereas brine is preferred in 5 km deep reservoirs, and the switchover point depends on reservoir conditions (e.g., geothermal temperature gradient). For indirect systems, subcritical, superheated, and supercritical organic Rankine cycles have been investigated (Wang et al., 2019). These systems have been integrated with auxiliary heat sources, including waste heat and solar energy (Garapati et al., 2020; Qiao et al., 2020). In both direct and indirect systems, a pump may be used to supplement the thermosiphon effect and enable sufficient flow rates. Other options to use CO_2 as a geothermal heat extraction fluid include integration with natural gas recovery (Ezekiel et al., 2020), which can have financial benefits but the net climate benefits need to be assessed, or implementation in depleted natural gas reservoirs, but higher residual brine saturations may lead to salt precipitation and inhibit the effectiveness of using CO_2 as a working fluid (Cui et al., 2021a).

Effective geothermal heat mining is essential to this approach. Geothermal power plants in hydrothermal resources may deplete the heat resource over time, as heat extraction exceeds the heat recharge by the geothermal heat flux, and can resort to additional strategies like injecting water to add pressure to the system (U.S. DOE EERE, 2021). The typical lifetime for geothermal power plants is on the order of a few decades and not much different from capital associated with other types of renewable and nonrenewable electricity-generating capacity. In the context of sedimentary basin CO_2-geothermal, in which conduction is the primary mode of heat transfer, (SedHeat, 2013) reservoir management may have added importance. Residual CO_2 trapping (which is a goal of GCS) must be accommodated while preserving sufficient CO_2 flow for heat extraction in the subsurface. Brine production for active CO_2 reservoir management (Buscheck et al., 2012), which typically manages reservoir pressure for GCS, could pull the CO_2 plume toward the production well to reduce the time until the produced fluid is predominantly CO_2. One modeling study suggests that the produced fluid must be at least 93% CO_2 for the use of CO_2 to be effective for geothermal heat mining (Garapati et al., 2015). In the operational phase, sedimentary basin CO_2-geothermal is contingent on the active management of injection and production flow rates, which implies management of heat extraction. Given the low-temperature (for geothermal systems) sedimentary resources, it could be preferable to use the CO_2-geothermal facility as a dispatchable resource (e.g., to firm variable wind and solar generation), as opposed to baseload operations that would deplete the heat too quickly. Attempting to optimally place and size wells—the choices of which will depend on the reservoir depth, temperature, thickness, permeability, and well configuration (Adams et al., 2021b)—can help facilitate effective geothermal heat mining and minimize water upconing in the production well (Ezekiel et al., 2022). As shown in Figure 3, inverted five-spots and circular horizontal well patterns are two design options that have been investigated in modeling studies (Garapati et al., 2015; Adams et al., 2021a,2021b; Randolph and Saar, 2011). The inverted five-spot configuration uses a center injection well, surrounded by four production wells. The circular horizontal configuration also has a center injection well but uses a circular collection well strategy that allows for broader heat capture. To fully realize the potential of the technology, it will be necessary to tailor the engineering and design of the wells, well pattern, and power plant system to the physical characteristics of the reservoir, as well as understand the thermodynamics of the mixtures of CO_2 with resident brine and how CO_2-water-rock interactions may impact long-term reservoir management strategies.

As the subsurface reservoir may be filled with brine at the outset of a new CO_2-geothermal project or contain residual brine if CO_2 has already been emplaced for GCS, the co-production of water and CO_2 in the production well may occur. Such co-production may promote corrosion in the well tubing and casing due to the acidic nature of the mixture, however, internal anticorrosion materials that are commonly used in the oil and gas industry may limit potential corrosion to be negligible (Cui et al., 2021a, 2021b). Numerical modeling has shown that production well design and managing pressure drawdown in the reservoir can limit water upconing in the production well (Ezekiel et al., 2022). Still, avoiding aqueous-free-phabse-CO_2 mixtures in the thermosiphon may be challenge, and wet CO_2 (CO_2 with dissolved H_2O) may be produced, which can result in higher fluid temperatures and pressures at the production wellhead due to the exothermic exsolution of H_2O from CO_2 (Fleming et al., 2020). The production of mixed fluids may reduce the thermosiphon effect because thermosiphons are stronger with the circulation of 100% CO_2 than of 100% H_2O (Buscheck et al., 2014), but the higher temperatures and pressures can increase electric power output by 15–25% compared to dry CO_2 (Fleming et al., 2020). Furthermore, if other acid gases are present in the injected CO_2 or the aquifer there will be additional challenges related to processing the produced CO_2 at the surface. Changes in reservoir petrophysical properties due to CO_2-water-rock interactions may affect heat mining, but reservoir simulations suggest that salt precipitation with continuous CO_2 injection may have more effect than geochemical reactions (Cui et al., 2018, 2021a, 2021b, 2018). Sedimentary formations can have heterogeneities in porosity, permeability, mineralogy, thickness, and other parameters, yet aside from one study on a multi-layered reservoir (Garapati et al., 2014), modeling to date has assumed homogeneous reservoirs with no variation in these reservoir properties. Because the geological heterogeneity of a reservoir can have a substantial impact on flow, productivity, and heat mining, investigating more complex systems in the context of geothermal heat extraction is a ripe area for research.

CO_2 BULK ENERGY STORAGE: THE STATE OF THE TECHNOLOGY

The combination of GCS and geothermal energy production can be designed to facilitate grid-scale energy storage. Such a CO_2 bulk energy storage (CO_2-BES) system could enable the deployment and utilization of high penetrations of variable wind and solar energy capacity. The original version of CO_2-BES was dubbed the "Earth Battery" (Buscheck, 2015). The Earth Battery combines sedimentary basin CO_2-geothermal with brine is production from the reservoir to manage pressure build-up from CO_2 injection and reduce the associated risks. In a sedimentary basin geothermal resource, the produced brine will be hot and could be used to generate electricity. With CO_2-BES, electricity on the grid is used to compress, inject, and re-inject CO_2 (and brine) into deep saline aquifers. Demand for this electricity could be timed to use excess wind and solar generation that would otherwise be curtailed. The compressibility of CO_2 provides exceptional energy storage capacity and CO_2 can function as a cushion gas (Buscheck et al., 2016). In this application, CO_2 would initially need to displace large quantities of brine, and then the brine and CO_2 injection/production would be managed for pressure containment. When electricity is needed, the pressurized and geothermally-heated CO_2 and brine can be produced from the reservoir to generate electricity. Of the total capacity of CO_2-BES designs with concentric rings and brine and CO_2 power cycles, as much as 93% of the total capacity is due to the brine cycle (Ogland-Hand et al., 2021). Further, the geothermal heat extraction can result in round-trip efficiencies much greater than 100%.

A CO_2-BES facility can be flexible and operate as energy storage, GCS, and a geothermal power plant (Ogland-Hand et al., 2021). The approach can thus firm variable wind- and solar-generated electricity and compensate for diurnal and weekly fluctuations in electricity demand, like those shown in Figure 1 (Ogland-Hand et al., 2019). This flexibility could also yield a more cost-effective utilization of transmission lines and greater power system reliability. As a result, CO_2-BES could be implemented to accommodate regional differences in renewable resource availability and electricity demand (Ogland-Hand et al., 2021), thereby enabling the displacement of fossil fuel-based generation across regional electricity systems. There are opportunities for this displacement to result in system-wide reductions in CO_2 emissions or water requirements but, as with other bulk energy storage approaches, such improvements in environmental outcomes are highly case-dependent (Ogland-Hand et al., 2019; Ryan et al., 2018; Hittinger and Azevedo, 2015).

Overall, CO_2-BES has promise, but more research is needed to better understand how to design and operate such systems—including the impacts of the choice of power cycle and its integration with the characteristics of the reservoir—to achieve financial viability. Initial studies of generic designs of CO_2-BES systems (i.e., not tailored to the geologic setting or the needs of the regional electricity system) estimate break-even compensation between \$8/tCO_2 and \$11/tCO_2 (Bielicki et al., 2021). This range is much lower than most estimates for the social cost of CO_2, suggesting that these systems would offer positive net benefits to society. Other designs that use transcritical and supercritical CO_2 in two-reservoir systems have been shown to have larger energy storage densities than compressed air energy storage (the only other subsurface bulk energy storage approach) (Liu et al., 2016). Although the use of compressed transcritical CO_2 for energy storage results in higher efficiencies and energy storage densities, these systems are more complex, require a much shallower low-pressure reservoir, and have yet to have their environmental performance investigated.

For CO_2-BES to be widely deployed, it will need to compete successfully against other energy storage options, such as pumped hydro storage and batteries. Pumped hydro storage is a mature technology that has been used for decades, but it requires suitable surface topography, elevation change, and reservoir capacity. The lack of availability of these factors limits the development of new projects. CO_2-BES has a synergy with GCS and can be located in areas that are not suitable for pumped hydro storage. Recent advances in lithium-ion batteries, as well as favorable public policies, have led to a rapidly increasing number of utility-scale projects. Current projects, however, have limited discharge duration of at most 10 h of storage (Ma et al., 2018) and continued expansion of batteries may introduce material supply chain constraints. Subsurface energy storage technologies like CO_2-BES are unlikely to rely on materials that are in limited supply, and offer the potential to provide long duration energy storage to compensate for regional and seasonal differences in variable renewable energy resources (Sepulveda et al., 2021).

THE POSSIBILITY FOR SEDIMENTARY BASIN CO_2-GEOTHERMAL AND CO_2-BES TO PROVIDE GIGATON REDUCTIONS IN CO_2 AND GIGAWATTS OF POWER TO THE GRID

Even with rapid rates of decarbonization, gigatons of CO_2 will still be emitted in the coming years. Sedimentary basin CO_2-geothermal and CO_2-BES are well suited to geologically store and utilize that CO_2, while providing valuable power system services that can offer the flexibility to integrate higher penetrations of variable renewables. Figure 4 provides an illustrative scenario to convey the potential scale of CO_2 emissions mitigation and power generation from these technologies.

In this scenario, the US power system is assumed to be fully decarbonized by 2035, consistent with goals expressed by the Biden Administration (The White House, 2021), which is achieved through a linear reduction of fossil fueled generation while not retiring existing hydropower, nuclear, and renewable capacity. In addition, 20 GW/yr of new wind power, with an average capacity factor of 35%, and 30 GW/yr of solar power, with an alternating current (AC) capacity factor of 23%, are added. These capacity additions exceed the maximum historical annual values by roughly 50% (Bolinger et al., 2020; Wiser et al., 2020). This scenario also assumes modest load growth consistent with electrification of 25% of light duty vehicle miles traveled. As shown in Figure 4A, wind and solar generation would contribute over half (54%) of the generation in 2035, which presents challenges in reliably operating the grid in all hours. Approximately 800 TWh are provided by undesignated carbon-free generation sources (''other''), which would likely need to provide the grid balancing services needed to integrate wind and solar power. Sedimentary basin CO_2-geothermal would be well-suited to contribute to help meet this gap.

To estimate the potential impacts of sedimentary basin CO_2-geothermal, Figure 4B shows the effect of five 100-MW plants becoming operational each year over ten years (i.e., totaling 5,000 MW). These power plants are assumed to have a 65% capacity factor (similar to natural gas combined cycle plants) to facilitate load following while still offering significant generation.

Although this scenario represents a rapid transition away from fossil fuel-based electricity production, the power sector still emits 1.4 GtCO_2 in 2021, and 10.2 GtCO_2 between 2021 and 2035. Such a draw-down period provides an opportunity for sedimentary basin CO_2-geothermal, which requires substantial quantities of CO_2 to ''prime'' the reservoirs before electricity can be generated (Ezekiel et al., 2022). Figure 4D shows the effect of priming each reservoir with 30 MtCO_2/yr for three years (based on Garapati et al., 2015).

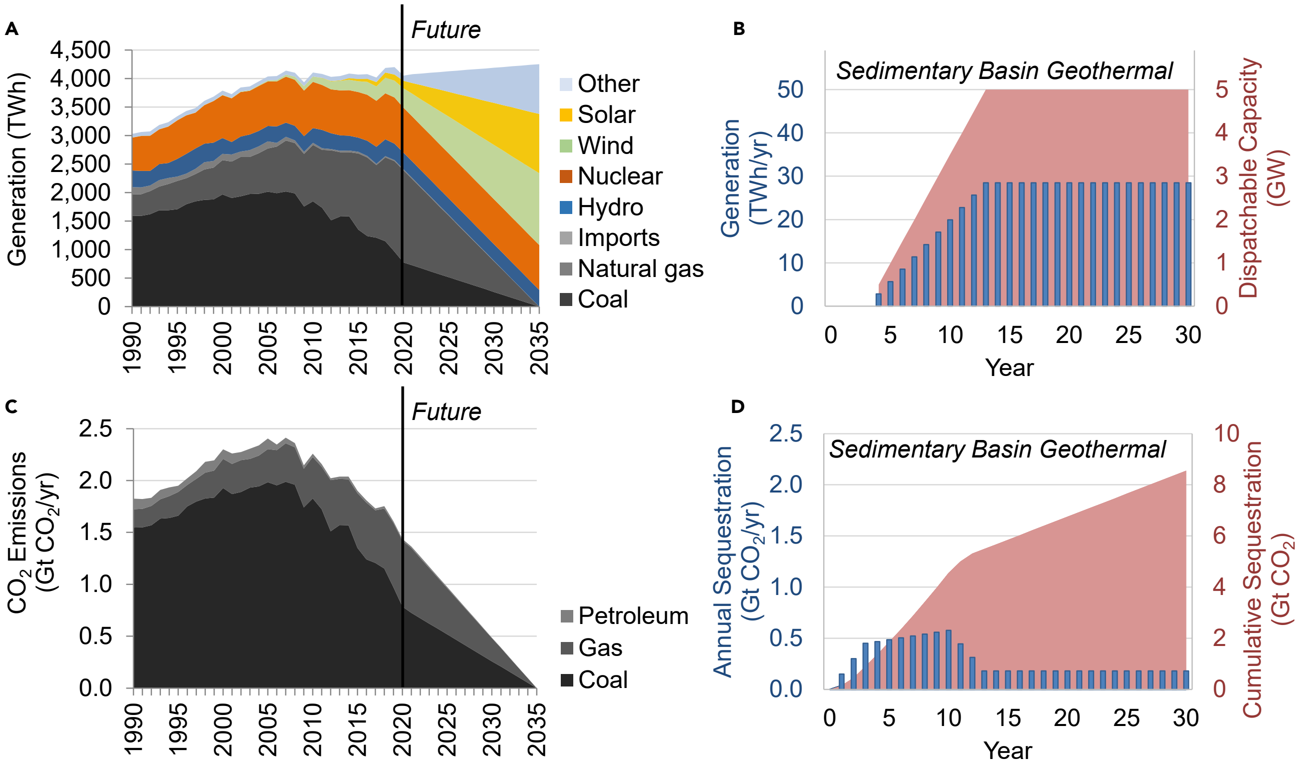

Figure 4. A simple scenario to illustrate rapid decarbonization of the power sector in the United States and the potential for sedimentary geothermal to geologically store CO_2 while providing power system benefits

(A) The mix of generation sources, (B) the estimated generation and firm capacity provided by fifty 100-MW sedimentary basin geothermal plants, (C) the power-sector CO_2 emissions from the combustion of fossil fuels, (D) the annual and cumulative CO_2 sequestered by the sedimentary basin geothermal plants.

Power generation commences afterward, with 4% of the CO_2 being replenished each year to accommodate losses in the reservoir.

Through this simple scenario, we show that these 50 sedimentary basin CO_2-geothermal facilities would help reduce greenhouse gas emissions through three mechanisms. First, they would geologically store 8 $GtCO_2$ over 30 years. Second, they would generate more than 600 TWh of renewable carbon-free electricity. Third, their 5 GW of capacity would be operated flexibly to help reliably integrate high penetrations of wind and solar power. As shown, the magnitude of GCS could be quite large relative to overall CO_2 emissions. The flexible power system capacity could also enable and support the integration of a substantial amount of variable renewable energy capacity. The direct generation from sedimentary basin CO_2-geothermal would be more modest in magnitude relative to more mature generation technologies, but still provide utility-scale levels of megawatt-hours.

Constructing 50 sedimentary basin CO_2-geothermal plants in 12 years (i.e., five GW of new firm capacity) would be an impressive scale-up, but such a rate of deployment is consistent with the trajectories of other energy infrastructure, including the construction of power generating capacity, wells, and pipelines. Wind power in the United States increased from 2.5 GW in 2000 to over 60 GW by 2012 and 122 GW in 2020 (Wiser et al., 2020) and moved from a minor contributor to one of the largest sources of new electricity on the grid. Although it is a more mature technology, 228 GW of natural gas generation capacity were added to the U.S. electricity grid between 2002 and 2016. With respect to the pace of drilling, there was a substantial increase in development of unconventional shale resources in the United States, which resulted in the addition of approximately 150,000 horizontal wells between 2005 and 2020. The United States also added over 1,000 miles of CO_2 pipelines between 2007 and 2020. Although each of these technologies is unique, the expansion of wind and natural gas generation, large-scale drilling, and pipeline construction demonstrate that rapid growth of energy infrastructure is possible under the right conditions.

Given the salient need for clear and sufficient policy and economic incentives to realize CO_2 emission reduction targets, sedimentary basin CO_2-geothermal and CO_2-BES provide unique opportunities to couple an increase in carbon-free electricity generation with GCS. Sedimentary basin CO_2-geothermal and CO_2-BES have the potential to be widely deployed at a scale sufficient to address the magnitude of the climate change challenge. Although neither technology has achieved wide commercial adoption, their development is sufficiently advanced such that near-term deployment is plausible and widespread adoption could be achieved in a time frame that matches the urgency of action needed for climate change.

SEDIMENTARY BASIN CO_2-GEOTHERMAL AND CO_2-BES WILL BE ENABLED BY A BROAD SET OF POLICIES AND MARKETS THAT SUPPORT RENEWABLE ENERGY, ENERGY STORAGE, CARBON MITIGATION, AND GEOLOGIC CO_2 STORAGE

The policy landscape that affects sedimentary basin CO_2-geothermal and CO_2-BES is complex, due in part to the range of services that they can provide. This section identifies how the development and deployment of these technologies can be accelerated through renewable energy mandates and incentives, energy storage requirements and market design, CO_2 taxes and emissions caps, and incentives for GCS. Differences in policies and market designs across countries and regions, in addition to the interactions and cumulative effects of relevant policies, will be consequential to the pace of demonstration and deployment.

Sedimentary basin CO_2-geothermal and CO_2-BES could be used to satisfy renewable energy mandates and benefit from renewable energy incentives, which have accelerated the deployment of wind and solar power capacity. In the United States, geothermal energy is broadly accepted in the state-level Renewable Portfolio Standards, which typically require that a percentage of electricity sales are provided eligible renewable energy technologies. Currently, 30 states and the District of Columbia have these mandates, which will require an estimated 630 TWh of generation by renewable sources by 2030 (Barbose, 2021). Similarly, the European Union's Energy Directive required 20% renewable energy by 2020, and growth to 32% by 2030 (and there are proposals to raise that target) (European Commission, 2021). In China, central planning resulted in rapid expansion of renewable generation capacity, provincial renewable obligations, and recent efforts to reduce renewable energy curtailment (Hove, 2020). Geothermal is also eligible for US federal subsidies, including the Investment Tax Credit and Production Tax Credit (NC Clean Energy Technology Center, 2021). Although sedimentary basin geothermal broadly meets the requirements for this suite of policies, it would also be appropriate to include CO_2-BES when geothermal heat extraction yields roundtrip efficiencies greater than 100%.

Numerous incentives, mandates, and favorable market structures for grid-scale energy storage are emerging, due to the value of its dispatchability and the declining costs of batteries, which could further the development and deployment of CO_2-BES. After California's pioneering energy storage mandate in 2013, five other US states have adopted energy storage mandates or targets by 2021 (U.S. DOE Energy Information Administration, 2021). In 2018, US regulators required power system operators to remove barriers for energy storage participation in energy, capacity, and ancillary services markets, with the expectation that tariffs will reflect the value of the services that storage can provide. (FERC, 2018) Given its potential for scale and performance, it is possible that CO_2-BES could help meet these energy storage mandates and participate in suitably designed power markets. The flexibility of CO_2-BES to operate as an energy storage system, a generation source, or both can result in challenges in appropriately compensating for services. The recognition of multiple value streams, some of which may be regulated while others are in competitive markets (Forrester et al., 2017), is essential for properly compensating the services provided by CO_2-BES.

Pricing CO_2 emissions, through a CO_2 tax or a cap-and-trade program (Aldy and Stavins, 2012), could benefit GCS as well as sedimentary basin CO_2 geothermal and CO_2-BES. Because CO_2 would be permanently stored with some of it circulated as a heat extraction fluid, the sale of CO_2 offsets or the generation of credits could provide revenue. In addition, incurring another cost when emitting CO_2 would disadvantage coal and natural gas-fired generation relative to geothermal generation. There are dozens of these market-based mechanisms worldwide, spanning regional, national, and subnational jurisdictions. For example, the European Union implemented an emissions trading system in 2005, which has grown considerably since then (The World Bank, 2021). In the United States, there are two major subnational CO_2 trading programs: (1) A cap-and-trade program in the state of California and (2) the Regional Greenhouse Gas Initiative that includes the Northeast and Mid-Atlantic states (Stavins, 2021). Although leakage from properly sited GCS reservoirs of any consequence (e.g., exceeds the US Department of Energy Storage Permanence goal (U.S. DOE, 2021)), is extremely improbable over operational lifetimes (Bielicki et al., 2015, 2016) and hundreds and thousands of years thereafter (IPCC et al., 2005; Pawar et al., 2015), sedimentary basin CO_2-geothermal or CO_2-BES operators would likely be required to conform to regulations governing GCS. For example, in the United States, the Environmental Protection Agency requires the GCS operator to monitor a GCS site for 50 years, or an alternative negotiated timeframe, after plugging the injection well before fully closing the site (U.S., Environmental Protection Agency, 2016).

Other policy instruments support GCS and are relevant for sedimentary basin CO_2-geothermal and CO_2-BES. For example, the US 45Q federal tax credit enhanced by the Inflation Reduction Act of 2022 (Yarmuth, 2022) provides incentives for the emplacement of CO_2 into geologic reservoirs (U.S. Department of Treasury, 2021; Esposito et al., 2019). The minimum amount of CO_2 captured depends on the type of facility, and the date-in-service of the equipment, and the value of the tax credit depends on the use of the CO_2: GCS, CO_2-enhanced oil recovery, or CO_2 utilization. For example, electric generating units with equipment placed in service on after December 31, 2022 must capture at least 18,750 tCO_2/y to be eligible for the credit, and can receive up \$85/tCO_2 for GCS. Direct air CO_2 capture (DAC), and other facilities can have lower annual capture requirements (1,000 tCO_2/y), and CO_2-enhanced oil recovery and other types of CO_2 utilization may receive a tax credit up to \$60/tCO_2. The Inflation Reduction Act of 2022 increases also 45Q credit values for any capture equipment placed in service after December 31, 2022 to \$180/tCO_2 for DAC facilities that store CO_2 in saline geologic formations, \$130/tCO_2 for DAC-utilization, and \$130/tCO_2 for DAC-EOR storage (Yarmuth, 2022).

The present structure has a \$25/tCO_2 difference between credits for storage and for utilization, but this difference increases to \$50/tCO_2 when the capture equipment is DAC. This is insufficient to encourage significant investment in direct storage and thus favors utilization projects such as CO_2-EOR or DAC-EOR that are profit generating. Sedimentary basin CO_2 geothermal and CO_2-BES would likely receive the utilization tax credit because they produce an economically valuable good (heat, electricity, and grid services), which can help recover fixed costs. In addition, those technologies can rely on a variety of sources for the CO_2 working fluid, but the ownership of the capture equipment influences the value of this tax credit. Specifically, tax credits could be claimed by the taxpayer owning the equipment to capture the CO_2, and the ability to monetize the tax credit with a third party opens new businesses for electricity companies, sedimentary basin CO_2-geothermal, and CO_2-BES systems.

Here, we described a variety of policies intended to spur renewable energy development, CO_2 emissions mitigation, and GCS, all of which could incentivize the development of sedimentary basin CO_2-geothermal and CO_2-BES. Because of this broad array of policies, these technologies may be able to collect multiple revenue streams and compete well against more mature technologies. In addition, sedimentary basin CO_2-geothermal can engender learning and reduce costs for GCS.

OVERCOMING THE OBSTACLES TO WIDESPREAD DEPLOYMENT

To achieve widespread deployment of sedimentary basin CO_2-geothermal and CO_2-BES several challenges should be considered, including technical, economic, and social issues that the GCS community has been examining extensively since the early 2000s. Examples specific to GCS include: preventing and monitoring CO_2 leakage from the target reservoir (Vialle et al., 2018); predicting subsurface flow of injected CO_2 (Nordbotten et al., 2005a, 2005b); CO_2 source-sink matching and transmission pipeline buildout (Bielicki et al., 2018); ensuring wellbore and pipeline integrity (Crow et al., 2010; Onyebuchi et al., 2018); public perception and acceptance (L'Orange Seigo et al., 2014); regulatory requirements, risk management, and long-term liability (Bielicki et al., 2016; Anderson, 2017; Dixon et al., 2015); inconsistent or absent markets that price CO_2 emissions (Aldy and Stavins, 2012); and economic competitiveness with other GHG mitigation approaches (Budinis et al., 2018; Lilliestam et al., 2012). Although these challenges also apply to sedimentary basin CO_2-geothermal and CO_2-BES, the goal of this perspective piece is to highlight the potential for combining GCS with renewable energy production and explore the unique challenges facing this new application of GCS. Some challenges that may be specific to these new technologies include controlling plume migration to allow for continuous CO_2 injection and extraction; ensuring efficient brine displacement and CO_2 heat sweep efficiency; and achieving CO_2 source-sink matching for non-continuous or non-uniform CO_2 injection demand. In addition, the success of these technologies is contingent on alignment of public policies, the availability of key incentives and participation in markets, and achieving public acceptance of large-scale projects. Although our simple scenario clearly demonstrates the potential of these technologies to enable significant decarbonization, there are several areas of research which, if well addressed, would help overcome the most pressing challenges. Here, we list seven outstanding multi-disciplinary research questions:

Major gaps in knowledge for sedimentary basin CO_2-Geothermal and CO_2-BES

1. What are the impacts on (multi-phase) fluid and energy flow due to geological heterogeneity at scales ranging from hydrostratigraphic layering to the pore scale and how do these impacts affect sedimentary basin CO_2-geothermal and CO_2-BES? Can the reservoir variability be leveraged to benefit the technologies?
2. What reservoir management strategies should be pursued to optimize the benefits of multi-decadal heat extraction?
3. What are the best deployment and operational strategies in light of decreasing sources of CO_2 and increasing penetrations of variable renewable energy on the grid?
4. How can life cycle assessment techniques be used to estimate the levels of decarbonization more accurately and determine the parameters that most greatly influence those outcomes?
5. What levels of incentives are necessary to encourage the growth of this industry and what conditions on these incentives would ensure the greatest levels of decarbonization?
6. What influences public support or opposition to the use of CO_2 for producing geothermal energy and how might this affect the technology deployment?
7. What are the technical and legal issues surrounding large-scale implementation of these technologies such as pressure or groundwater level changes extending over multiple pore-space owners across the whole basin?

Subsurface heterogeneity can play an important role in heat transfer, but these issues are not fully understood and could impact the performance of facilities. Candidate aquifers in sedimentary basins can have unconformities in three dimensions and the permeability, for example, can vary by several orders of magnitude over a few meters in all directions. The existence of such heterogeneity can create ''thief zones'' of higher permeability, with higher mass flow rates (and thus more heat extraction with if there is sufficient residence time in the reservoir), or regions with lower permeability that can restrict flow rates, increase pore pressure, and negatively impact heat extraction efficiency. At the reservoir-scale, there are important, but unanswered questions regarding optimal rates of heat extraction. There is incomplete understanding of the ongoing CO_2 replenishment rates required to maintain geothermal power generation levels, which could present opportunities for additional GCS or challenges in maintaining geothermal energy production, depending on the access to CO_2 supplies. To date, these reservoir characteristics and the subsequent effects on the operational costs of energy production and roundtrip efficiencies of energy storage have not been considered. All of these issues, and more, exist within uncertain long-term CO_2 mitigation measures and in the context of evolving power systems that are subject to changing regulatory, policy, and business landscapes. If these obstacles are overcome, these technologies could provide gigaton-level CO_2 mitigation and gigawatt-level power system services.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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