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Paving the way for CO_2-Plume Geothermal (CPG) systems: A perspective on the CO_2 surface equipment

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ABSTRACT

Subsurface reservoirs play an important role in decarbonizing the energy sector, be it through geothermal energy production or carbon capture and storage. In recent years, there has been an increasing interest in CO_2-Plume Geothermal systems, which combine carbon sequestration with geothermal, using CO_2 instead of water as a subsurface heat and pressure energy carrier. Since CO_2-Plume Geothermal systems are added to full-scale CO_2 Capture and Sequestration operations, all of the initially injected CO_2 is ultimately stored. CO_2-Plume Geothermal, therefore constitutes of both CO_2 Capture Utilization as well as Storage. This paper assesses the huge technical potential of this technology, identifying a potentially highly relevant market for CO_2 equipment manufacturers and discusses the current research demand, based on the current state of the art of CO_2 equipment. Both temperature and pressure levels are significantly lower than CO_2 turbine designs investigated and proposed so far for other applications, such as waste heat recovery. For a depth of 5 km, a typical one-stage radial turbine design might have a rotational speed of 23'000 rpm to 42'000 rpm and an impeller diameter between 96 mm to 155 mm. Together with technology-specific requirements, due to produced fluid impurities, it becomes evident that significant further development efforts are still necessary.

1. CO_2-Plume geothermal: current status and research demand

A fundamental and rapid transformation of the global energy system is necessary to limit global warming to 1.5 °C or at least slightly above. This includes a major expansion of various renewable energy sources such as solar, wind and geothermal. The geothermal sector experiences a strong increase with respect to installed capacities worldwide [1] and ongoing research activities, such as the potential future utilization of hot dry rock (HDR) systems [2]. Against the background of increasingly uncertain global supply chains, geothermal energy can be a promising local energy source for heating and power generation [3]. At the same time, almost all of the Intergovernmental Panel on Climate Change (IPCC) transformation pathways to limit global warming to 1.5 °C require the future use of large-scale carbon capture and storage (CCS) technologies [4]. Although the expansion of renewable energies and the development of a CCS infrastructure can, of course, happen separately, a technology that can combine both necessary aspects into one concept would be of great benefit. Such a true CO_2 Capture Utilization and Storage (CCUS) concept can enhance the economic performance of CCS projects since it provides energy in the form of electricity and/or heat. CO_2-Plume Geothermal (CPG) systems, which will be explained in more detail in the following chapter, can combine both aspects of a true CCUS system: large-scale and ultimately long-term to permanent sequestration of all of the initially injected CO_2 and utilization of the CO_2 in the form of electricity generation with a CO_2 turbine [5]. Applying CO_2 as an energy carrier for geothermal systems has various advantages as outlined later in detail within Chapter 2. The source for the CO_2 can be either direct air capturing (DAC) [6], industrial processes [7] or power plants [8]. Considering that most DAC capturing processes require a certain heat demand for the internal regeneration, geothermal energy can be a promising source to provide both the required heat and power for the process as well as to store and/or utilize the captured CO_2 [9]. The general promising features of CPG-based CCUS hub, also in combination with industrial CO_2 sources, are outlined in detail within two case studies for India [10] and the Baltic Region [11]. A detailed overview on the possibilities for CCUS

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in medium-temperature geothermal reservoirs is presented by Vulin et al. [12].

Parallel to the increasing interest in CCS/CCUS and in using CO_2 as an energy carrier in geothermal systems, it is also strongly investigated as an attractive working fluid for closed-loop power plant processes [13]. Commonly discussed conventional application areas for CO_2 power plants are industrial waste heat recovery [14], bottoming gas-turbine cycles [15] and concentrated solar power plants [16]. A detailed overview of different cycle concepts for those potential heat sources is presented in the review by Crespi et al. [17]. The growing interest can also be seen in the increasing number of large-scale experimental activities for CO_2 compressors [18] and turbines [19]. Therefore, on the one hand, a strong commercialization drive exists regarding CO_2 turbines and CO_2 compressors (for both CO_2 power plant cycles and CO_2 injection projects). On the other hand, especially regarding the operational conditions of CO_2 turbines, strong deviations between the temperature and pressure levels at the turbine inlet and outlet exist. Both pressure and temperature at the turbine inlet are significantly lower than for the standard sCO_2 system (e.g. for waste heat recovery), and the CO_2 within the open CPG system will contain impurities, for example, in the form of liquid water. Thus, while the CO_2 turbines currently being developed and tested provide a suitable starting point, they may not be directly applicable to potential future CPG power plants without further development. While this paper will discuss the research demand for CPG-specific equipment in detail, the following subsection provides a detailed overview of the main research activities in the CPG field in general.

In 2011, Randolph and Saar [5] introduced a novel concept for combining geothermal energy production with geological carbon dioxide sequestration. The authors named their concept *CO_2-Plume Geothermal* and clearly distinguish their approach from CO_2 based Enhanced Geothermal Systems (EGS), for which the use of CO_2 as an energy carrier is also discussed e.g. by Brown [20] or Zhou et al. [21]. In the following years, the research focus was mainly on further identifying the most pivotal impact parameters on the system's performance and novel advanced system concepts. Randolph et al. [22] carried out a detailed modeling of the wellbore heat transfer in CO_2 systems and concluded that in general adiabatic well flow can be considered in future system studies. Another paper by Randolph et al. [23] studied the impact of the potential heat extraction on the reservoir pressure buildup during CO_2 sequestration operations, revealing that it can decrease overpressurization by more than 10%. Another important parameter for the system performance is the injection temperature since a higher injection density can result in a significantly higher net power output [24,25].

Further studies focused on the heat extraction characteristic in multi-layered reservoirs [26]. One further milestone on the pathway towards a better understanding of the CPG characteristic and its comparison to conventional brine systems were the studies by Adams et al. [27,28]. The results demonstrated that the significant CO_2 density change in this process creates a buoyancy-driven thermosiphon and that CO_2 has a reservoir pressure drop approximately 3–12 times less than brine [27]. Furthermore, the well diameter has a pivotal impact on the achievable net power output and CO_2 produces more power at shallower depths and lower permeabilities than brine [28]. Thus, it can outperform the conventional geothermal power generation concept for low- and medium-enthalpy systems using a binary cycle such as an Organic Rankine Cycle (ORC) for power generation [29].

In addition, Adams et al. [28] showed that a so-called pumped CPG system, which uses a pump/compressor to increase the CO_2 mass flow rate next to the thermosiphon effect, can result in a significantly higher achievable net power output. Another study confirmed the favourability of CO_2 compared to water as an energy carrier for different geological conditions in Mexico [30]. Further studies investigate the CPG application potential in depleted gas [31] or oil reservoirs [32]. The authors examine the influence of economic factors on the system profitability and conclude that the net CO_2 storage income is the most crucial economic variable to de-risk the investment. An in-depth assessment of the behavior of large-scale CO_2 storage in deep saline aquifers is presented by Wang et al. [33] for a case study in Wyoming, USA. Norouzi et al. [34] carried out a detailed numerical analysis for a 3D braided fluvial aquifer and identified the optimal CO_2 mass flow rate for maximizing the system's net power output. Also, the recent work by Okoroafor et al. [35] applies a 3D numerical reservoir simulator to study the impact of several parameters on the CPG injectivity and productivity indices. The result showed that the top of the reservoir, the porosity, and the formation thickness display the highest impact on the CPG performance.

Considering the critical comparison between water and CO_2, CO_2 might be significantly more favorable in larger scale reservoirs, especially when they display a high heat transfer area and low matrix permeability [36]. The recent study by Antoneas and Koronaki [37] focuses on the application of CPG in smaller energy communities, while other studies investigate the promising concept of off-shore CPG systems [38]. Regarding the environmental assessment of CPG, the recent work by Liu et al. [39] investigates several scenarios for CPG systems with various CO_2 sources. The findings reveal that the life cycle greenhouse gas (GHG) emissions of CPG systems range from −0.25 to −6.18 kg CO_2/kWh, thus, displaying a positive environmental impact of this technology. Two studies by Ciu et al. highlight the promising potential of using CO_2 for heat extraction from depleted gas reservoirs [40] and weakly consolidated sandstone reservoirs [41]. Furthermore, several recent studies indicate the potential of CPG for either combined heat and power generation [42] and for the possibility of using CPG systems for flexible power generation [43,44]. Buscheck et al. [45] presented an advanced CPG concept to harvest, store, and dispatch energy from surface (solar, nuclear, fossil) resources and provide flexibility services to the grid by this concept. Thus, next to the general advantage of geothermal energy being base-load capable, CPG can also provide the increasingly required flexibility services to a future electrical grid supplied mainly by fluctuating renewable energy sources such as wind or solar. Another novel approach might be the combination of hydrogen production with CPG, as outlined in a recent study for Saudi-Arabia [46]. Recently, a proof of concept of a stable circulation due to the CO_2 thermosiphon in a former oil and gas field was reported [47]. Over 25 days a stable pressure difference of 14 bar between production and reinjection well was achieved. While this step is an important first milestone for a future commercial, large-scale CPG projects, a larger field demonstration is the next step in de-risking commercial CPG operations.

In summary, the available literature on CPG systems significantly increased during the last decade and addresses detailed aspects, such as detailed reservoir studies or advanced system concepts. However, the main focus of the existing literature lies clearly on subsurface-related research questions. Despite a study by Tang et al. [48] on the potential design for a CO_2-water separator, literature is currently not discussing the market potential and necessary development needs and potential design for CPG-specific surface equipment, mainly the compressors and turbines. While this is, on the one hand, justifiable due to the high uncertainties regarding the underground behavior of the CO_2, reliable and optimized surface plant components are also crucial for the first possible CPG pilot and demonstration projects. A critical discussion of the component specific development needs, which could result in future design- and Computational Fluid Dynamics (CFD) studies of CPG turbines, as already existing for conventional geothermal turbines (cf. [49]), is pivotal for the further development of the CPG technology. Therefore, the outlined research gap is the motivation of our work and aims to provide a first indication of the potential development needs and component designs for CPG systems.

This paper addresses several aspects: First, we provide a compact overview of the CPG technology and the resulting operational conditions for CO_2 turbines. Second, we assess the technical potential of the

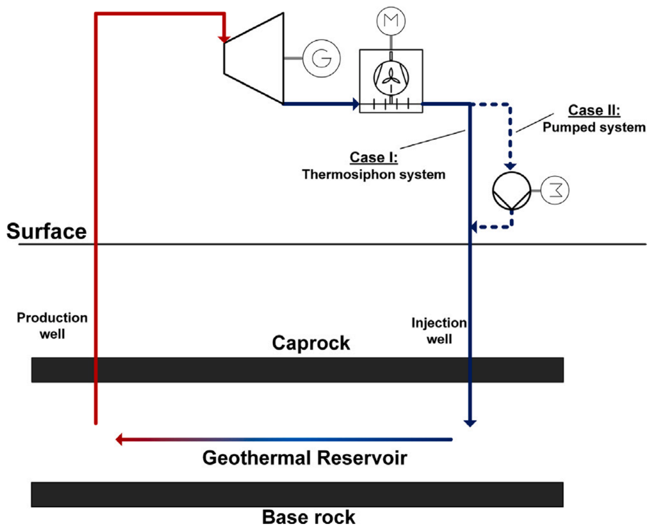


Fig. 1. General working principle of a CPG system.

CPG technology, identifying a potentially highly relevant market for CO_2 equipment manufacturers. Finally, we discuss the current research demand, based on the current state of the art of CO_2 equipment, considering the significantly different operational characteristics within a CPG system, compared, for example, with an industrial waste heat recovery CO_2 power plant. While there are several in-depth design studies on CO_2 compressors [50], turbines [51] and heat exchangers [52] for other applications, such studies are still missing for CPG applications. Thus, we present, for the first time, a compact overview of CPG's market potential and future research demand, with a focus on the CPG surface equipment. Although no new numerical results are presented here, this work contributes to science and industry by pointing at avenues for potential future research activities and economic developments concerning the entire CO_2 equipment market by discussing their operational conditions in detail.

2. Working principle of CPG

The basic principle of the CPG technology is shown in Fig. 1. Similar to in CCS, CO_2 is injected in a naturally permeable reservoir at e.g. 2 to 5 km depth. However, in the case of CPG, the geothermally heated CO_2 is then back-produced, expanded through a turbine, cooled, and re-injected into the original CO_2 storage reservoir. As the mass of CO_2 contained within surface facilities at any time is insignificant, all the CO_2 is stored just like a purely CCS project [5].

The primary advantage of using CO_2, compared to water, is its favorable mobility (the inverse of kinematic viscosity), enabling higher mass flows through the reservoir than for liquid water, all else being equal. This mobility effect dominates over the reduced specific heat capacity of CO_2 compared to H_2O at relevant reservoir pressures and temperatures, thereby increasing the geothermal energy extracted from the subsurface. Favorably, even at relatively shallow reservoir depths, CPG power generation can take place directly in a turbine, while a conventional water/brine geothermal system would require an Organic Rankine Cycle (ORC) as a binary cycle. Another benefit from using CO_2 is the thermosiphon effect [27], due to the large difference in density of cold CO_2 in the injection well as opposed to the hot CO_2 in the production well. This results in a difference in gravitational head that contributes to the pressure differential in the reservoir required to make the CO_2 flow, leading to reduced pumping requirements to circulate the CO_2. The lower fluid densities and gas-like properties in the production well lead to higher wellhead pressures compared to CO_2. After the expansion in the CO_2 turbine, the CO_2 is cooled and (depending on the pressure level) condensed for re-injection into the original reservoir, so that ultimately all CO_2 is permanently stored.

In order to provide better visualization of the different process steps within a CPG system, Fig. 2 visualizes the general temperature-entropy and temperature-density diagram. The temperature-entropy diagram visualizes the significant increase of the CO_2 within the reservoir. Within the production well, the temperature of the CO_2 drops significantly due to its gas-like behavior (cf. [27]). The temperature-density diagram visualizes the significant difference between the average density in the production and injection well, which is one of the main driving forces for the potential thermosiphon operation. However, as it can be seen in both Figs. 1 and 2(b), next to the thermosiphon operation also a pumped CPG operation can be considered. As shown in detail by Adams et al. [28], such a pumped CPG system, which uses a pump/compressor to increase the CO_2 mass flow rate next to the thermosiphon effect and enables a lower turbine outlet pressure, can result in a significantly higher achievable net power output. While on the one hand, the pumped CPG displays a higher auxiliary power for the operation, the higher achievable mass flow rate and turbine pressure differential result in a higher net power output.

As the CO_2 produced from the reservoir is directly expanded in the CO_2 turbine, liquid water and other fluids are likely to enter the turbine along with the CO_2. While such liquid water in a CO_2 turbine constitutes a potential problem, it is not unsurmountable, as the density of liquid water of about 1000 kg/m^3 is only about a factor of 2.5 higher than the typical density of CO_2 of about 400 kg/m^3 when produced from typical reservoirs considered for CPG [53]. As the fluid flow rate through the turbine should be maximized, one design option is to allow some water ingestion into the turbine. Thus, a goal of CO_2 turbine development for CPG power plants is to develop turbines that can tolerate a significant amount of liquid water, together with mostly CO_2. The free-phase liquid water can stem from two sources, namely (1) from flow from the reservoir into the production well and (2) from exsolution of water from the CO_2 in the production well, as the CO_2 rises in the production well and as pressure and temperature decline, decreasing the water solubility index in the CO_2. This water exsolution is an exothermic reaction, providing up to 41% additional power to CPG power plants under the conditions investigated by Fleming et al. [53]. In summary, CPG power plants yield increased thermal (and thus electric) power, compared to groundwater-based geothermal power plants due to (1) the higher mobility of CO_2, compared to water, under typical CPG-reservoir conditions, more than making up for the reduced specific heat capacity of CO_2 compared to water under those conditions, (2) the thermosiphon effect and (3) exothermic water exsolution from CO_2 in the production well during the ascent of CO_2 that has water dissolved in it, as is typically the case when water-bearing geologic reservoirs are used for CCS and CPG operations.

Since most of the current publications focus on the conceptual investigation of the overall system and the impact of the subsurface conditions (permeability, etc.), detailed investigations and designs regarding the surface component have not been carried out. E.g. regarding the isentropic turbine efficiency, most recent studies assume a value of 78% (e.g. Adams et al. [54] and Ezekiel et al. [55]), which was initially introduced in one of the first CPG-specific publications by Adams and Kuehn [56]. Gladysz et al. [57] assume a turbine efficiency of 85%. For the CO_2 cooler/condenser, an approach temperature of 7 K is one of the most commonly used assumptions [28]. A detailed overview about the modeling methodology for CPG systems can be found in the detailed publication by Adams et al. [58], who present the open-source model genGeo combined with extensive explanations for applied the modeling approaches and assumptions. The actual extracted heat from the geothermal reservoir depends mainly on the number of wells and the corresponding CO_2 mass flow rate (cf. Section 3). However, several studies report the expected thermal efficiency of CPG systems. E.g. Hansper et al. [59] and Schifflechner et al. [42] report thermal efficiencies between 5 and 8%, indicating the ratio between the

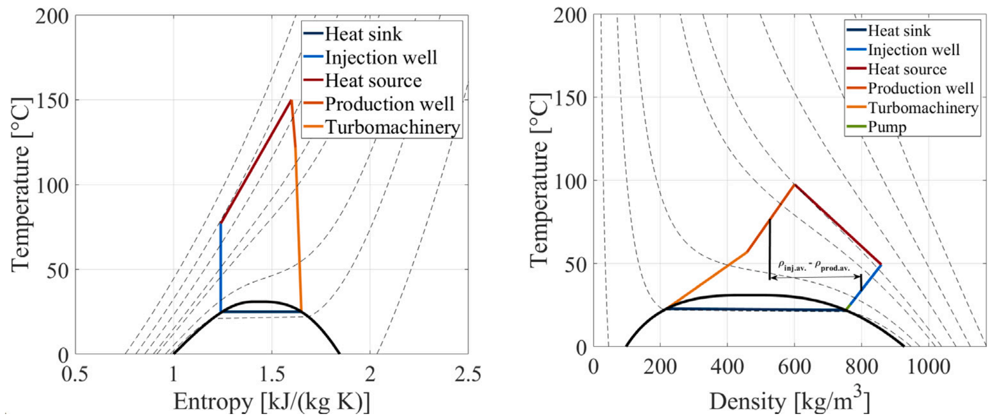


Fig. 2. General (a) temperature-entropy diagram of an un-pumped CPG system and (b) temperature-density diagram of a pumped CPG system.

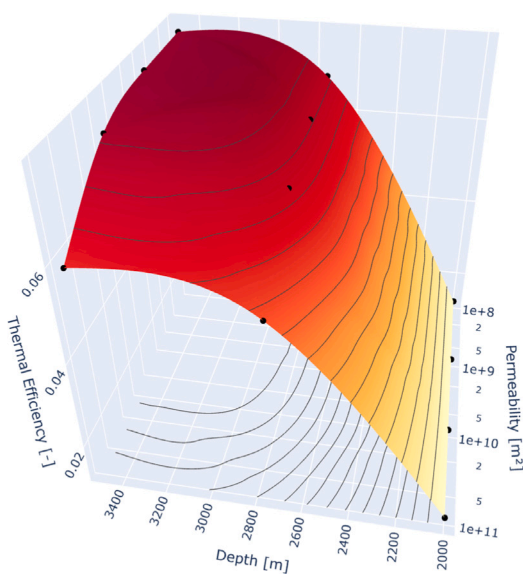


Fig. 3. Estimated thermal efficiency of a CPG system.

achievable net power output and extracted heat from the geothermal reservoir. The thermal efficiency is defined by the subsequent equation.

$$\eta_{th} = \frac{P_{el,net}}{\dot{Q}_{CO_2,res}} \tag{1}$$

As it can be seen exemplary in Fig. 3 the achievable net thermal efficiency mainly depends on the reservoir depth. For a depth of 3000 m or more, thermal efficiencies above 6% can be achieved. While the permeability has a strong effect on the extractable amount of heat (cf. [28]) it has no significant impact on the efficiency itself. This general plot was created by using the open-source genGeo model [58]. In order to provide the reader also some potential in-depth insights on the actual CPG system parameters for different depths, Fig. 7 in Appendix presents the temperature-density and temperature-density diagram for 2000 and 3500 m depth.

3. The potential of CPG

CPG is applicable in a broad range of geologic reservoirs where geologic CO_2 storage is considered, ranging from depleted oil and gas fields (both on- and offshore) to, in particular, deep saline formations. Adams et al. [58] demonstrate that using CO_2 as a subsurface heat extraction fluid, compared to water, decreases the cost of geothermal electricity across most geologic conditions. The reservoir temperature and transmissivity, which is the product of reservoir permeability and thickness, are the most sensitive parameters that drive the performance of CPG. The sensitivity analysis by Ezekiel et al. [60] for CPG operations after enhanced gas recovery (EGR) also shows that, as expected, high reservoir temperatures are critical for geothermal power generation. However, they also show that the next most sensitive CPG parameters after temperature are the well diameter, followed by the ambient air heat rejection temperature, the permeability anisotropy, the horizontal permeability and finally the relative permeability of the geologic reservoir.

Comparing the levelized cost of electricity (LCOE) for both energy carriers (CO_2 versus water) at different reservoir depths (and thus different hydrostatic fluid pressures) and reservoir transmissivities reveals that the favorability of CO_2 depends on several factors, such as depth [58]. At shallower reservoir depths (i.e. lower reservoir temperatures and pressures) and a given transmissivity, the LCOE of CPG is lower than that of H_2O. At greater reservoir depths (i.e. higher reservoir temperatures and pressures), the difference reduces, but overall more power is produced, while the LCOE reduces further. While a single well pattern produces a power output of a few MW_e [28], a larger field development, combining numerous such well patterns, results in a much larger combined power output in the range of several dozen MW_e or more [59]. As shown by Boehmer et al. [61] for different promising geological settings in North America, the net power output of large-scale systems might be between 200 and 700 MW_e. The power can be either produced by multiple smaller CO_2 turbines distributed over the areal extent of the field (which is multiple square kilometers) or from a large-scale central power plant. The optimal mass flow rate of the CPG system depends also on several factors, such as reservoir transmissivity, reservoir depth or well diameters. As shown exemplary for one well pair in Fig. 4, there is one optimal CO_2 mass flow rate resulting in the highest possible net power output. While higher mass flow rates increase on the one hand, the power generation potential, the available turbine pressure differential decreases and the power demand for the cooling system increases. Thus, high mass flow rates do not necessarily provide the highest possible power output.

Regarding the thermo-economic performance of CPG systems, the LCOE can only be estimated with high uncertainties since a first real-world large-scale CPG demonstrator is still missing. Furthermore, due to the significant amounts of CO_2 required for such systems, the transportation and potential purchase costs or achievable revenues by storing the CO_2 will have a pivotal impact on the economic performance. Due to high uncertainties regarding future CO_2 prices, these costs are currently neglected in most papers (e.g. in [59]). Wang et al. [62] present a thermo-economic optimization of a large-scale direct supercritical CO_2 electric power generation system, while not calling it directly CPG. Their findings for a depth of 2500 m indicate achievable

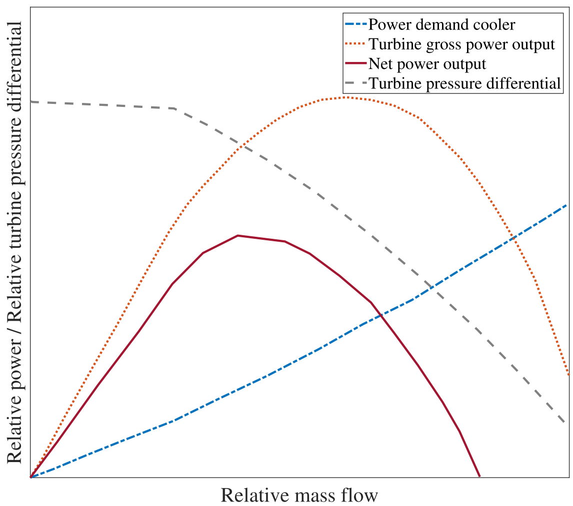


Fig. 4. Relative behavior of the power output and turbine pressure differential for increasing CO_2 mass flow.

LCOE between 190 and 170 \$/MWh$_e$, depending on the plant capacity. Their economic models suggest rather similar investment costs for both the surface plant capital and geothermal wells. For a CO_2-EGS system, both Gladysz et al. [63] and Tagliaferri et al. [64] present a detailed thermo-economic evaluation. Depending on the particular scenario, the share of the surface equipment on the overall investment costs is between 20 and 55%. Langenfeld and Bielicki [65] investigate aquifers in Wyoming (United States) for their thermo-economic potential for CPG application. They identified more than 80 promising aquifers with achievable LCOEs between 200 and 250 \$/MWh$_e$. McDonnell et al. [66] evaluate the potential performance of a CPG site in a sandstone reservoir in the West of Germany. For the base case scenario they report achievable LCOE of 60 \$/MWh$_e$ while considering also potential supporting grants by the government and additional revenues due to the CO_2 storage. Hansper et al. [59] report achievable LCOE of a CPG brownfield system between 120 and 200 170 \$/MWh$_e$. Sudhoff et al. [25] evaluate the achievable LCOE for different numbers of wells and reservoir types. The results indicate a quite large range between 36 and 194 \$/MWh$_e$ with minimal achievable LCOE of 36 \$/MWh$_e$.

Ogland-Hand et al. [67] reveal that CPG could approximately triple the United States geothermal electricity power capacity just by one single CPG “sweet spot” in South Dakota, but the necessary breakeven electricity price for an economic investment might be this development is on the order of 200 \$/MWh$_e$. A study of the saline formations in the United States suggests an economic potential of 200 GW$_e$ considering greenfield projects (no existing infrastructure assumed) and LCOE below 100 \$/MWh$_e$ [58]. Considering that the currently installed worldwide ORC capacity is around 4 GW$_e$ [68], CPG has the potential to be a highly relevant market for manufacturers of CO_2 turbines, compressors and other relevant equipment such as heat exchangers or cooling/condensing towers. Furthermore, in general CPG might result in a better economic performance than sole CCS or conventional geothermal systems, since they enable a double source of revenue by the CO_2 storage and the heat and/or power production [69].

4. Operational characteristics and research demand of surface equipment for commercial CPG systems

The recent review by White et al. [13] provides a detailed overview of the current general trends and research demands for CO_2 power systems. However, the review is not addressing CPG and its individual requirements and challenges. Therefore, the following section focuses on the operational characteristics and research demands for CPG-specific surface power plant equipment.

The CO_2 turbine for the CPG process needs to be designed for the thermal conditions at the design point, has to cope with load point variations throughout the year and with the composition of the fluid produced from the well, depending on the level of processing upstream of the turbine, as discussed briefly at the end of Section 2. The design point of the turbine in terms of pressure and temperature varies with the reservoir depth with wellhead exit pressures between 100 bar to 230 bar and wellhead exit temperatures between 45 °C to 130 °C (see Fig. 5). The condenser determines the back-pressure, which is normally around 57 bar to 62 bar, depending also on the approach temperature of the cooling/condensing tower system. For a reservoir depth of 5 km, the CO_2 expansion process results in an isentropic enthalpy drop of 56 kJ/kg. A typical radial turbine design can convert this enthalpy difference into mechanical work within one stage, with a circumferential velocity of around 240 m/s. The associated centrifugal force induces a mechanical strain well below typical steel yield strengths. The circumferential Mach number gives a good indication for aerodynamic design aspects. In this case, the circumferential Mach number is close to unity (Ma = 0.96) at the impeller inlet, thus, requiring a careful aerodynamic design. A two-stage design might be desirable to achieve higher flexibility, such as to cope with decreasing condenser pressures.

With the given mass flowrate, an initial design can be computed, exemplarily for a potential typical mass flowrate of 150 kg/s (cf. [28]) and for a reservoir depth of 5 km for the design of an CO_2 turbine. For this case, a typical one-stage radial turbine design has a rotational speed of 23’000 rpm to 42’000 rpm and an impeller diameter between 96 mm to 155 mm, meaning that the design has certain degrees of freedom. Both the turbine rotational speed and its size are feasible and the margins to rotodynamic, structural dynamics and manufacturing limits are large enough to cope with the lowest and largest assumed mass flowrates. Alternatively, also a multi-stage axial turbine is possible. While the volume flowrate changes marginally for reservoirs at shallower depths, the enthalpy differences during expansion in the turbine decrease from 56 kJ/kg to 11 kJ/kg. This results in a lower rotational speed of around 10’000 rpm. Next to the inlet pressure conditions, the turbine inlet temperature can also strongly impact the achievable mass-specific power output. Considering the same in- and outlet pressures of a turbine, a higher inlet temperature results in a significantly higher turbine outlet power.

As outlined later in the paragraph, the load point in terms of mass flowrate and/or turbine back pressure can change through the year and over the years as reservoir temperatures and pressures decline due to energy extraction. Using a wet-bulb cooling tower might ensure a condensation of the CO_2 over the whole year, however, this may come with a water demand that could be economically and environmentally challenging in dry areas. Thus, while air-cooled coolers/condensers, often employed by geothermal power plants, have no water consumption, they can only cool but not condense the CO_2 during certain periods in the summer, depending also on the climate at a given geographic power plant location, affecting not only the turbine outlet conditions but also the performance characteristic of the overall CPG system itself. Therefore, to extract a maximum of available work with the turbine, measures to adjust the turbine for seasonally changing heat rejection temperature conditions must be taken. A combination of speed control and adjustable guide vanes gives flexibility but comes with investment cost, especially for the speed control. Current research suggests that system design codes with integrated turbomachinery models allow determining the required control interventions and help to determine the trade-off between investment for control measures and increased work output. When considering turbine costs it is also critical to keep in mind that turbine components (e.g. blades) may degrade relatively quickly in open power loop systems (i.e. CPG), where impurities (e.g. liquid water, but potentially also H_2S) are produced from the geologic reservoir along with the CO_2. While these impurities (which have to be removed

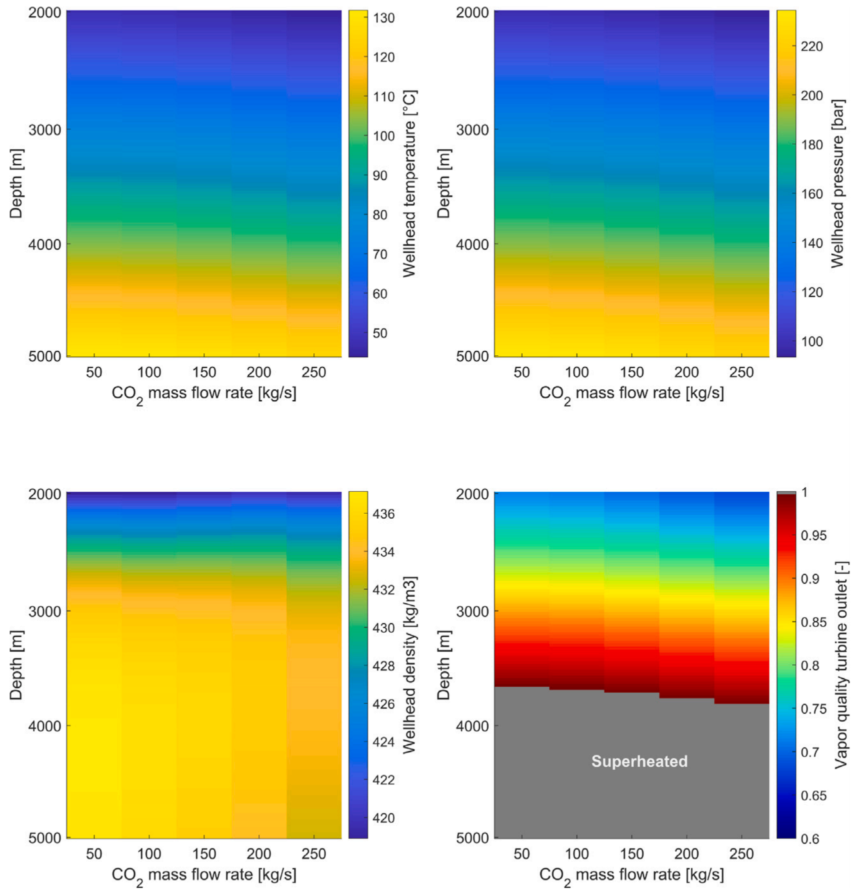


Fig. 5. Summary of the turbine operating conditions, considering the turbine inlet temperature, turbine inlet pressure, turbine inlet density and turbine outlet conditions.

before CO_2-reinjection to maintain a high injectivity index of the CO_2 injection well) could be removed upstream of the turbine, this comes with power generation penalties (see also end of Section 2).

Other aspects to consider are the possibilities and challenges associated with an expansion into the two-phase CO_2 flow region as well as the composition of the fluid leaving the well and eventually entering the turbine. Expanding into the two-phase flow region gives the system designer more freedom during the design phase. Expanding into the two-phase flow region can also allow higher enthalpy drops in the turbine. For example, for the 2 km deep reservoir case, already 35% of the CO_2 is condensed at the turbine outlet. Another possible scenario can be decreasing ambient temperatures, which lower the condenser back pressure accordingly. As shown in Fig. 5, the vapor quality of the CO_2 at the turbine outlet increases with higher reservoir depths and is superheated for deep CPG systems. Thus, the two-phase expansion and its potential impact on the turbine design is mainly relevant for rather shallow CPG systems.

A certain expansion into the two-phase flow region might be allowed without any harmful concomitants. A further reduction of the outlet pressure results in the formation of droplets accompanying the expansion into the two-phase region. These droplets might lead to liquid film formation on the rotor and the formation of so-called secondary droplets that lead to droplet impingement erosion. Little knowledge is available for condensation at high expansion rates as typical for turbines at high pressures, even less for CO_2 and only a few studies exist for radial turbines. Research is required on this process that eventually leads to design guidelines. Such design guidelines might limit the allowed liquid content or provide measures to prevent droplet erosion, e.g., hardening of the steel in certain areas where droplet impact is to be expected. Thus, the likelihood of implementing technical measures that allow a higher liquid content also depends on how high the achievable additional power output is. Table 1 presents the reduction of the achievable turbine power output for various depths and different maximum allowed at the turbine outlet. The numbers highlight that especially for shallow depths up to 2500 m, a limitation of the allowed liquid content at the turbine outlet can result in a power reduction between 12 and 37%. For deeper CPG systems, the threshold value of the liquid limit has only a minor impact on the achievable turbine power.

Table 1
Reduction of the achievable power output in case of a maximum liquid content level at the turbine outlet limiting the achievable outlet pressure.

Depth	No liquid allowed	Max. 5%	Max. 10%	Max. 15%
2000 m	36.37%	35.23%	33.28%	30.21%
2500 m	21.38%	19.38%	16.57%	11.88%
3000 m	11.72%	8.82%	4.22%	–
3500 m	3.94%	–	–	–

The impact of liquid in any form in the fluid leaving the well on the turbines must be treated carefully. At the current state of research, the liquid needs to be separated before the fluid enters the turbine, reducing the turbine mass flowrate and thus power output (see also end of Section 2). The separation process is associated with an inevitable pressure loss which can be avoided if the turbine withstands the liquid. Research suggests that distinct regions with droplet erosion can be identified in which steel hardening might reduce the erosion process to an acceptable value [70]. Thus, while the presence of e.g. natural water increases the CPG surface power plant complexity, its exothermic exsolution in the production well can result in significantly higher wellhead temperatures and pressures, increasing the achievable power output of the system [53]. Non-condensable gases, such as methane,

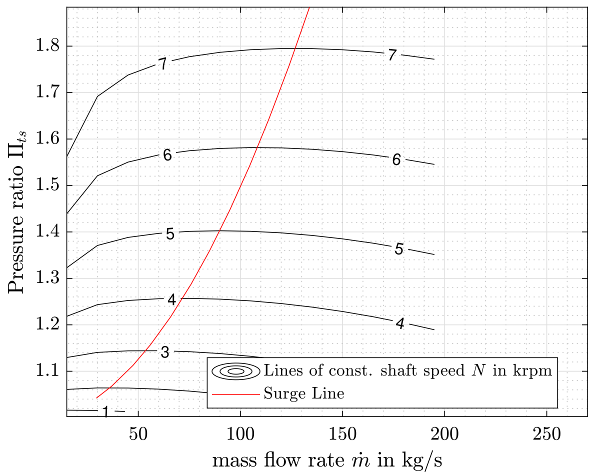


Fig. 6. Potential performance map of a CPG-specif CO_2 compressor.

potentially produced (in small quantities) during CPG operations after enhanced gas recovery (EGR) in the fluid are not harmful to the turbine but change the enthalpy drop for the given pressure ratio. Such variations in the fluid composition can be mitigated with the control interventions.

As outlined previously, using a compressor or pump can support the thermosiphon effect in CPG. The benefit can be readily investigated with compressor models integrated into the system design program. Such compressor models are available for CO_2. The design can be carried out with a two-zone model [71] before the performance at different load points is evaluated with mean-line analysis [72]. Such models have already been validated for particular CO_2 compressors [73] and provide a solid basis for optimizing CPG systems. For instance, Fig. 6 displays the performance map generated with a mean-line tool for CPG system with a reservoir depth of 2.5 km and the same reference parameters as by Hansper et al. [59]. Such a performance map is used in the first iteration of a system analysis. In turn, the system analysis provides the required operational parameters for the compressor and an updated performance map is generated. In the end, for instance, the circumferential Mach number, which results in the lowest LCOE, is a result. These are not necessarily within the experimentally validated range and can initialize further research needs. A point often discussed is the formation of a two-phase flow in the impeller with an impact on performance and durability.

The previous section provides a summary of the special operating conditions of potential CPG specific turbines and compressors. Considering the stated existing CO_2 designs, summarized by White et al. [13], highlights that the CPG application is characterized by significantly lower turbine temperatures and pressures than those addressed in the literature so far. Thus, while the current research activities on CO_2 turbines for other applications, such as waste heat recovery, provide a profound basis for the development of CPG-specific CO_2 turbines, future research activities are required, as the existing designs and activities cannot be directly applied to a CPG system due to the different operational conditions and the likely impurities within the CO_2 stream.

5. Conclusion and outlook

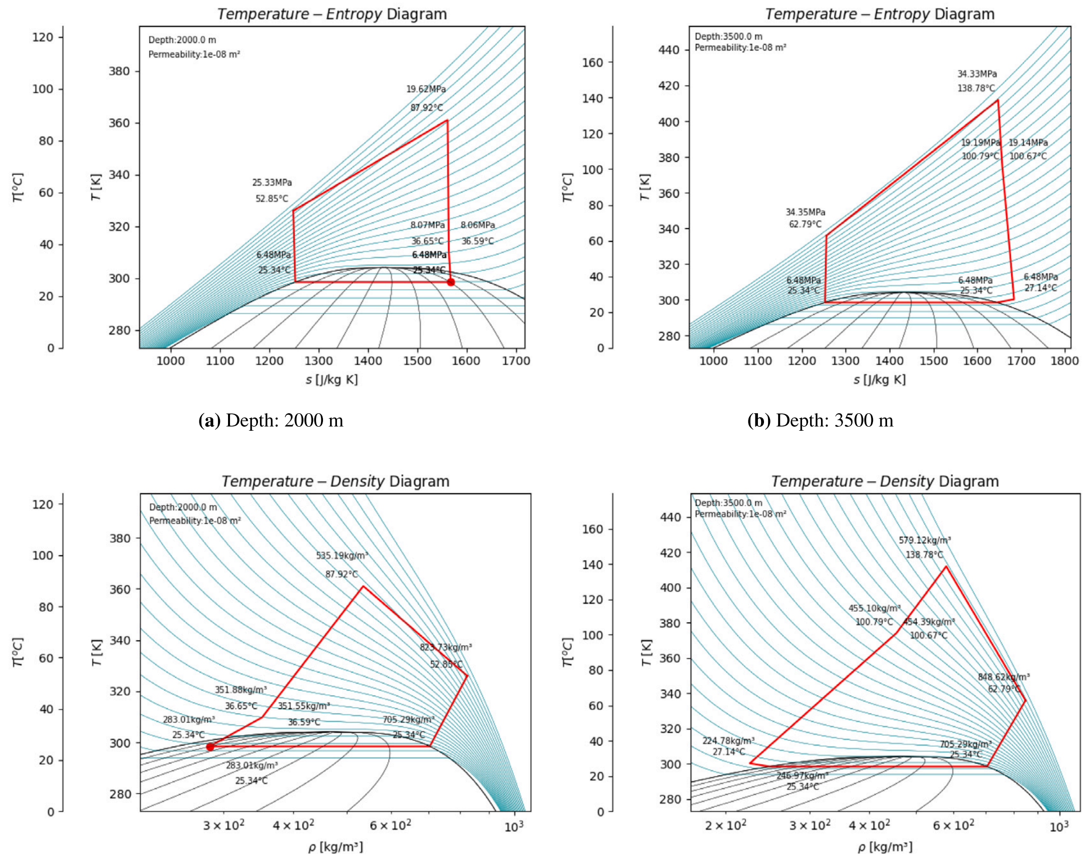
This work presents a compact overview of the working principle of the CPG technology and its technical potential. The operational conditions, resulting requirements, and research demand for CPG-suitable CO_2 turbines in particular, are discussed. The main findings are:

- CPG can combine both aspects of a true CCUS system: large-scale storage of all CO_2 and utilization of the CO_2 in the form of electricity generation with a CO_2 turbine.
- CPG can be applied in a wide range of subsurface settings, ranging from saline formations to depleted oil and gas fields. Techno-economic analyses indicate a large potential application field for this technology (estimated at several hundred GWe), translating to a sizable market for CO_2 equipment.
- The design point of the turbine in terms of pressure and temperature varies with the reservoir depth with wellhead exit pressures between 100 bar to 230 bar and with wellhead exit temperatures between 45 °C to 130 °C.
- Both temperature and pressure levels are significantly lower than CO_2 turbine designs investigated and proposed so far for other applications, such as waste heat recovery. Together with CPG-specific requirements, due to produced fluid impurities, it becomes evident that significant further development efforts are still necessary regarding future commercial CPG CO_2 turbines.
- For a depth of 5 km, a typical one-stage radial turbine design has a rotational speed of 23’000 rpm to 42’000 rpm and an impeller diameter between 96 mm to 155 mm might be applied.
- For shallow depths up to 2500 m, limiting the allowed liquid content at the turbine outlet would result in a power reduction between 12 and 37%. For deeper systems, the threshold value of the liquid limit has only a minor impact on the achievable turbine power.

In conclusion, this work provides a comprehensive discussion of the market potential and development needs of CPG-specific surface equipment, especially regarding the turbine this. While existing research on waste-heat recovery and concentrated solar applications are currently resulting in strong development and commercialization of CO_2 turbines, the significantly lower temperature and pressure levels for CPG applications require further development needs. Therefore, there is the need for further CPG-specific equipment design studies and techno-economic optimization studies focusing also on the off-design performance and the optimal design point for the CPG equipment. This will pave the way for successful and optimized first large-scale demonstration projects in the future.

Nomenclature

Abbreviations	
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CFD	Computational Fluid Dynamics
CPG	CO_2-Plume Geothermal
DAC	Direct Air Capturing
EGR	Enhanced Gas Recovery
GHG	Greenhouse Gases
HDR	Hot Dry Rock
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Costs of Electricity
ORC	Organic Rankine Cycle
Subscripts	
e	Electric
net	Net power
res	Reservoir
th	Thermal
Symbols	
N	Shaft speed, rpm
$\dot{m}$	Mass flow, kg/s
$\dot{Q}$	Heat flow, kW
P	Electric power, kW
η	Efficiency, - or %



(a) Depth: 2000 m (b) Depth: 3500 m

(c) Depth: 2000 m (d) Depth: 3500 m

Fig. 7. Temperature-entropy and temperature-density diagrams for 2000 and 3500 m depth.

CRediT authorship contribution statement

Christopher Schifflechner: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Formal analysis, Conceptualization. **Jasper de Reus:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Sebastian Schuster:** Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Andreas Corpancho Villasana:** Writing – review & editing, Visualization, Software. **Dieter Brillert:** Writing – review & editing, Supervision. **Martin O. Saar:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Funding acquisition, Conceptualization. **Hartmut Spliethoff:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Fig. 7 presents the temperature-density and temperature-density diagram for 2000 and 3500 m depth. These plots were created by using the open-source genGeo model and the main assumptions outlined in the corresponding publication [58].

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