David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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c/ Porvenir, 27 - 41013 Sevilla.
Tlfs.: 954 487 447; 954 487 451; Fax: 954 487 443
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The potential of CO_2-Plume Geothermal (CPG) Systems for CO_2 component manufacturers: opportunities and development needs

Christopher Schifflechner[1,*], Jasper de Reus[2], Hartmut Spliethoff[1], Martin O. Saar[2,3], Sebastian Schuster[4], Dieter Brillert[4]

[1] *Chair of Energy Systems, School of Engineering and Design, Technical University of Munich, Garching, Bavaria, Germany*
[2] *Chair of Geothermal Energy and Geofluids, Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland*
[3] *Department of Earth and Environmental Sciences, 116 Church Street SE, Minneapolis, MN 55455, USA*
[4] *Chair of Turbomachinery, University of Duisburg-Essen, 47057 Duisburg, Germany*

*Corresponding Author: c.schifflechner@tum.de

ABSTRACT

Subsurface reservoirs play an important role in decarbonizing the energy sector, be it through geothermal energy production or carbon capture and storage (CCS). In recent years, there has been an increasing interest in CO_2-Plume Geothermal (CPG) systems, which combine CCS with geothermal, using CO_2 instead of water as a subsurface heat and pressure energy carrier. As explained later in the paper, applying CO_2 as a subsurface working fluid can be more efficient than water as it has a higher mobility (inverse kinematic viscosity) and as its large thermal expansion coefficient results in a thermosiphon effect that reduces the pumping power required. CO_2 can also directly be utilized in a turbine for power generation. Furthermore, since CPG systems are added to full-scale CO_2 Capture and Sequestration operations, all of the initially injected CO_2 is ultimately stored. CPG therefore constitutes of both CO_2 Capture Utilization as well as Storage. 400

This paper assesses the huge technical potential of the CPG 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. 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.

1 INTRODUCTION AND SCOPE OF THIS PAPER

A fundamental and rapid transformation of the global energy system is necessary to limit global warming to 1.5ºC or at least 2.0ºC. This includes a major expansion of various renewable energy sources such as solar, wind and geothermal. At the same time, almost all of the IPCC transformation pathways to limit global warming to 1.5ºC require the future use of large-scale carbon capture and storage (CCS) technologies (Greig and Uden, 2021). 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 to achieve revenues. 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 form of electricity generation with a CO_2 turbine (Randolph and Saar, 2011). Applying CO_2 as an energy carrier for geothermal systems has various advantages as discussed in Chapter 2.

Parallel to the increasing interest in the use of 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, for example, for industrial waste heat utilization (White et al., 2021). The growing interest can also be seen in the increasing number of large-scale experimental activities for CO_2 compressors (Hacks et al., 2018) and turbines (Moore et al., 2018). Therefore, on the one hand, a strong commercialization drive exists for both CO_2 turbines and CO_2 compressors (for both sCO_2 power plant cycles and CO_2 injection projects). On the other hand, especially under the operation 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.

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 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 sCO_2 power plant. Thus, we present, for the first time, a compact overview about CPG's market potential and future research demand, with a focus on the CPG surface equipment. Although no direct 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.

2 WORKING PRINCIPLE OF CPG

The basic principle of the CPG technology is shown in Figure 1. Similar as in CCS, CO_2 is injected in a naturally permeable reservoir at e.g. 2 to 5 km depth. However, in 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 so that all CO_2 is ultimately permanently stored underground (Randolph and Saar, 2011). 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 sCO_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 (Adams et al., 2014), 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 H_2O. 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. Figure 2 visualizes the general temperature-entropy and temperature-density diagram of a CPG system. 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 sCO_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 sCO_2 of about 400 kg/m^3 when produced from typical reservoirs considered for CPG (Fleming et al., 2020). As the fluid flowrate through the turbine should be maximized, the water is ideally not removed before the turbine. Thus, a goal of sCO_2 turbine development for CPG power plants is to develop turbines that can tolerate significant amount of liquid water, together with mostly sCO_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 sCO_2 in the production well, as the sCO_2 rises in the production well and as pressure and temperature decline, decreasing the water solubility index in the sCO_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. (2020). 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 sCO_2, compared to water, under typical CPG-reservoir conditions, more than making up for the reduced specific heat capacity of sCO_2 compared to water under those conditions, 2) the thermosiphon effect and 3) exothermic water exsolution from sCO_2 in the production well during the ascent of sCO_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. (2021b) and Ezekiel et al. (2020)), which was initially introduced in one of the first CPG-specific publications by Adams and Kuehn (2012). Gladysz et al. (2020) 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 (Adams et al., 2015). 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. (2019) and Schifflechner et al. (2022) report thermal efficiencies between 5 and 8 %, indicating the ratio between the achievable net power output and extracted heat from the geothermal reservoir.

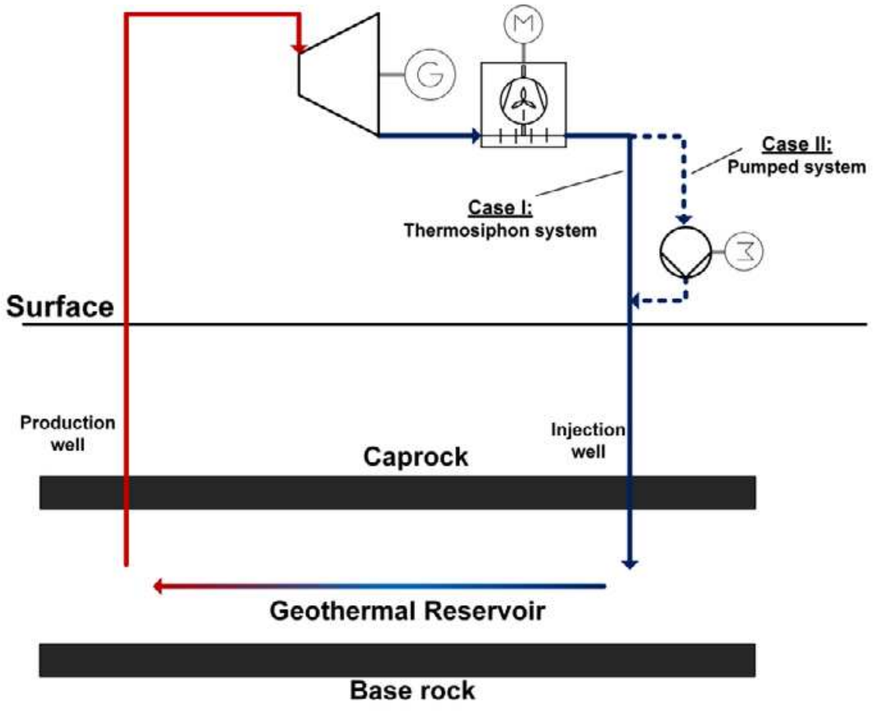

Figure 1: General working principle of a CPG system

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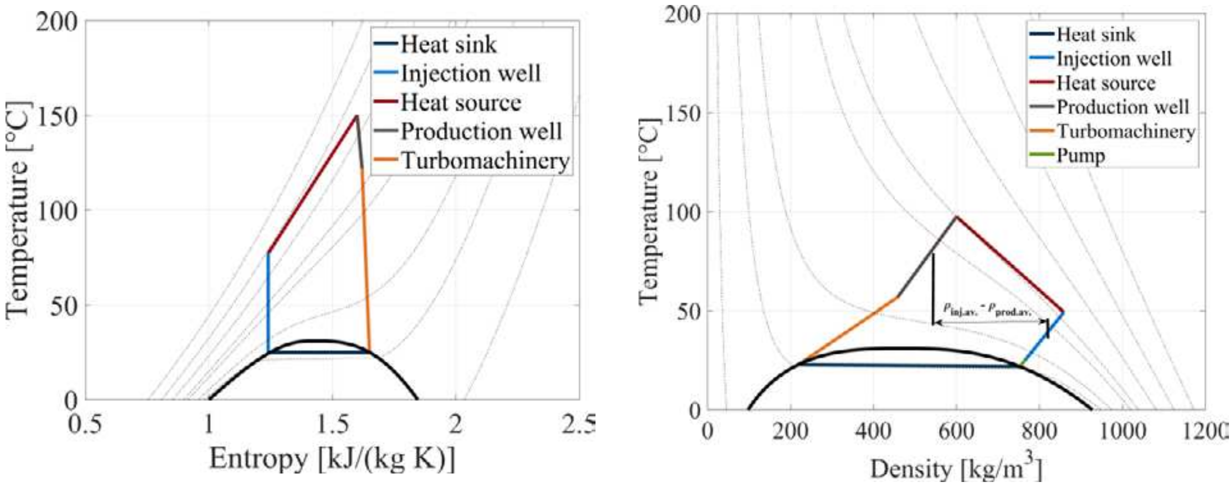

(a) (b)

Figure 2: General (a) temperature-entropy of a thermosiphon system and (b) temperature-density diagram of a pumped CPG system

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., 2021a) 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 CPG sensitivity analysis by Ezekiel et al. (2021) 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 (sCO_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 (Adams et al., 2021a). 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 (Adams et al., 2015), 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 (Hansper et al., 2019). The power is 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 CO_2 turbine at a 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 Figure 3, 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 are not necessarily providing 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. Hansper et al., 2019). Wang et al. (2022) 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 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 sCO_2-EGS system, Gladysz et al. (2020) 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 (2017) 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. (2020) 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. (2019) report achievable LCOE of a CPG brownfield system between 120 and 200 170 \$/MWh$_e$. Sudhoff et al. (2019) 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$_e$.

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$_e$ (Adams et al., 2021a). Considering that the currently installed worldwide ORC capacity is around 4 GW$_e$ (Wieland et al., 2023), CPG has the potential to be a highly relevant market for manufacturers of sCO_2 turbines, compressors and other relevant equipment such as heat exchangers or cooling/condensing towers.

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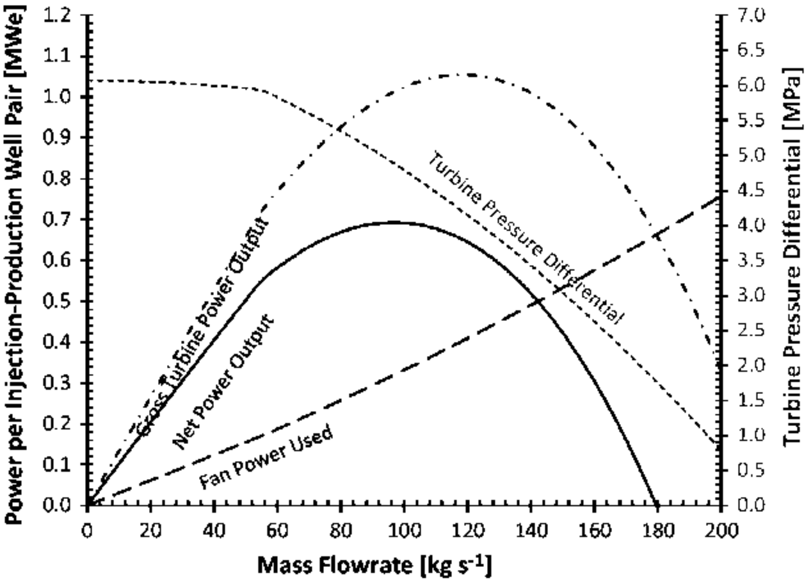

Figure 3: Exemplary power output of a direct CO_2 thermosiphon (un-pumped) system for one injection–production well pair (figure taken from Adams et al. (2015))

4 OPERATIONAL CHARACTERISTICS AND RESEARCH DEMAND OF SURFACE EQUIPMENT FOR COMMERCIAL CPG SYSTEMS

The recent review by White et al. (2021) provides a detailed overview of the current general trends and research demands for sCO_2 power systems. However, the review is not addressing CPG and its individual requirements and challenges. Considering the limited space for the work here, the following section focuses on the operational characteristics and research demands for CPG-specific surface power plant equipment.

The sCO_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 Figure 4). 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 sCO_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.

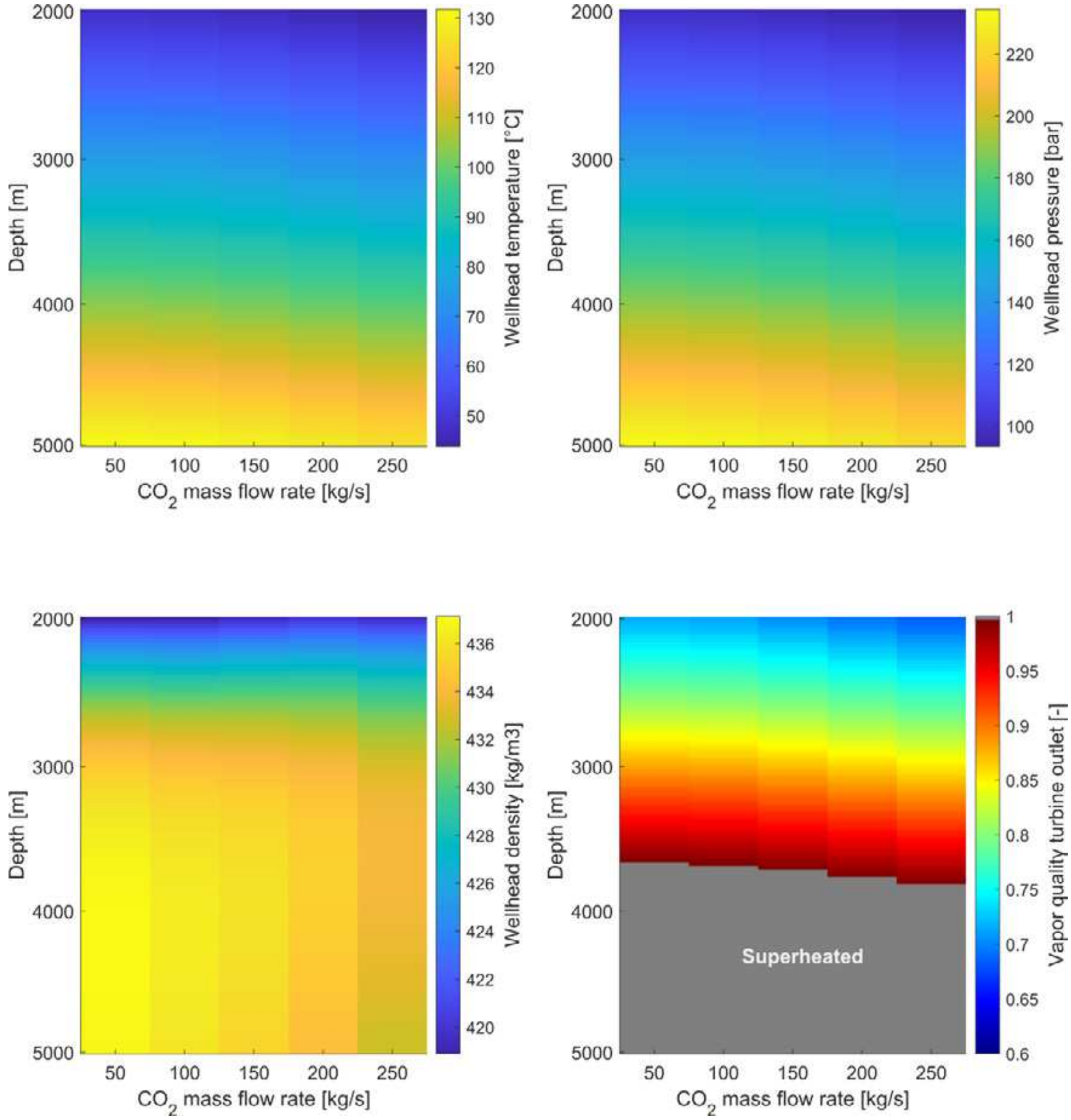

Figure 4: Summary of the turbine operating conditions, considering the turbine inlet temperature, turbine inlet pressure, turbine inlet density and turbine outlet conditions.

With the given mass flowrate, an initial design can be computed, exemplarily for a potential typical mass flowrate of 150 kg/s (cf. Adams et al. (2015)) and for a reservoir depth of 5 km for the design of an sCO_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. A multi-stage axial turbine is also possible. The volume flowrate changes marginally for reservoirs at shallower depths, however, the enthalpy differences during expansion in the turbine decrease from 56 kJ/kg to 11 kJ/kg (cf. Schifflechner et al. (2023)). 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 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 Figure 4, 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 - commonly quantified with the subcooling - can 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 subcooling or provide measures to prevent droplet erosion, e.g., hardening of the steel in certain areas where droplet impact is to be expected. 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 (Wittmann et al., 2022). 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 (Fleming et al., 2020). Non-condensable gases, such as methane, 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.

The previous section provides a summary of the special operating conditions of potential CPG specific turbines. Considering the stated existing CO_2 turbine designs, summarized in the recent review by White et al. (2021), 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 & 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: **407**

- 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 GW_e), 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.

First, large-scale demonstration projects are necessary regarding the potential future market uptake of CPG. Recently, a proof of concept of a stable circulation due to the CO_2 thermosiphon in a former oil and gas field was reported (Böhmer et al., 2022). 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. A joint industry-academic CPG consortium has been initiated by the ETH Zurich for this purpose.

Next to reliable base load power generation, CPG power plants can also be applied for combined heat and power generation (Schifflechner et al., 2022) or to provide flexible power generation (Fleming et al., 2022), thereby also supporting only intermittently available energy resources, such as wind and solar power (van Brummen et al., 2022). Therefore, especially considering CPG systems in Central Europe, these advanced conceptual aspects should be addressed in more detail within future studies.

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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