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# $CO_2$ Plume Geothermal (CPG) Systems for Combined Heat and Power: Opportunities and Challenges

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## ABSTRACT

In recent years, there has been an increasing interest in $CO_2$ Plume Geothermal (CPG) systems, which is an attractive approach to combine CCS with geothermal energy production. Applying $CO_2$ as the heat carrier fluid can be more efficient than water since it displays higher mobility and a higher thermal expansion coefficient. While CPG systems are highly attractive for sole electric power generation in former oil and gas fields, they could also be applied in regions with higher population densities for combined heat and power generation (CHP). To increase public acceptance and support the decarbonization of the heating sector, CHP CPG systems might be an attractive concept for selected CPG sites. This work investigates the potential benefits and challenges of CPG systems for CHP applications compared to geothermal systems using water/brine as the subsurface heat carrier. Two different CPG CHP configurations are evaluated for a reference case with a depth of 4.5 km and a required district heating network supply temperature of 80°C. The application of a CHP system reduces the achievable net power output compared to a sole power generation system. While a thermosiphon system displays a net power reduction of 11 %, a significantly higher net power output decrease of around 32 % can be observed for a pumped CPG system. Comparing both investigated CHP options reveals the favorability of a CHP layout with heat extraction on an intermediated pressure level. Thus, despite the higher plant complexity, this option can result in significantly higher power output and achievable revenues. Furthermore, the required reservoir depths for both water and $CO_2$ are evaluated concerning different district heating supply temperatures and heat demand as well as geothermal gradients. Depending on the assumed boundary conditions, a CPG system requires a higher reservoir depth between 800 and 1100 m compared to a system using water as a heat carrier. Thus, CPG CHP can only be applied to locations with promising geological settings in a sufficient depth.

## 1. INTRODUCTION

Deep geothermal energy can play a substantial role in decarbonizing both the heating and electric power sector. Both recent studies by Lund and Toth (2021) as well as Huttrer (2020) demonstrate the strong growth of the worldwide installed capacity for geothermal direct use and power generation, respectively. In addition to the technically established conventional utilization of hydrothermal reservoirs, during the last years, there has been an increased focus on innovative approaches, such as advanced systems with closed loops (cf. (Malek et al., 2021)) or the use of $CO_2$ as a heat transfer medium. Especially the utilization of geothermal resources while using $CO_2$ instead of water as a heat carrier has gained substantial attention from both academia and industry. Using $CO_2$ as the subsurface working fluid enables higher heat extraction rates and efficiencies due to the higher mobility (inverse kinematic viscosity) of $CO_2$ (Randolph and Saar, 2011). Additionally, the large thermal expansion coefficient of $CO_2$ results in a strong thermosiphon effect that reduces or eliminates parasitic pumping power requirements (Adams et al., 2014). $CO_2$ can be used as the geothermal energy extraction fluid in both Enhanced Geothermal Systems (EGS) (cf. Brown (2000) and Atrens et al. (2011)) and in $CO_2$ Plume Geothermal (CPG) systems (Randolph and Saar, 2011). Since CPG systems use naturally permeable formations, they do not require resolving the existing major technical and socio-political obstacles that EGS face. Moreover, anticipated typical CPG systems yield significantly more (thermal electric) power than envisioned typical $CO_2$-EGS due to EGS' limited resource size (small artificially generated reservoirs) and due to limited advective heat transfer through fracture-flow-dominated "reservoirs" (Randolph and Saar, 2011). Furthermore, since CPG systems are added to full-scale $CO_2$ Capture and Sequestration (CCS) operations and since they ultimately store all of the initially injected $CO_2$, they result in full-scale geologic $CO_2$ storage and constitute $CO_2$ Capture, Utilization and Storage (CCUS) systems. The results by Garapati et al. (2015) demonstrate that CPG systems could operate long-term for both scenarios, either with a constant ongoing $CO_2$ sequestration or a finite amount of $CO_2$. CPG systems also have a promising potential to provide flexible power generation (Fleming et al., 2022; van Brummen et al., 2022). A detailed assessment of the achievable net power output and optimal $CO_2$ flow rate for a CPG system in a fluvial aquifer is presented by Norouzi et al. (2023).

While a full CPG demonstration project is still pending, several experimental activities were carried out in order to investigate the real behavior of a $CO_2$ thermosiphon flow under real operational conditions and site characteristics. In 2015 at the SECARB Cranfield Site, a first field test of a $CO_2$ thermosiphon in a partially saturated reservoir with a depth of around 3 km took place. The results are presented and discussed in detail by Pan et al. (2018). While a thermosiphon flow could be initiated by venting, the $CO_2$ flow rate steadily declined over time. Thus, the findings revealed that a sustainable long-term thermosiphon operation was not possible for the given system conditions. More recently, an important proof of concept has been achieved in a doublet system within a former oil and gas field in Europe

(Böhmer et al., 2022). The results demonstrate that the system was able to provide a stable pressure difference on the surface, which could be used for power generation.

So far, CPG research has focused mainly on solely electric power generation. This focus is appropriate when either rural areas like former onshore oil and gas fields or offshore applications are considered. Nevertheless, for regions with higher population densities, assessing and optimizing the thermodynamic and economic potential of CPG systems for combined heat and power generation (CHP) is highly relevant: First, in order to provide a significant contribution towards the required decarbonization of the heating sector. Second, to increase the local public acceptance of geothermal energy and potentially also of CCS, given that CPG utilizes the $CO_2$ and ultimately stores all of the $CO_2$ underground, thereby constituting a true, combined CCUS system. As Bielicki et al. (2023) highlight, CPG can also be installed at strategic locations close to large-scale industrial $CO_2$ sources and/or locations requiring flexible power systems. Hau et al. (2021) studied the potential of a CPG system in Switzerland, demonstrating the interest in CPG systems within geographic settings that are promising for geothermal CHP systems due to the potential high heating demand during the winter period.

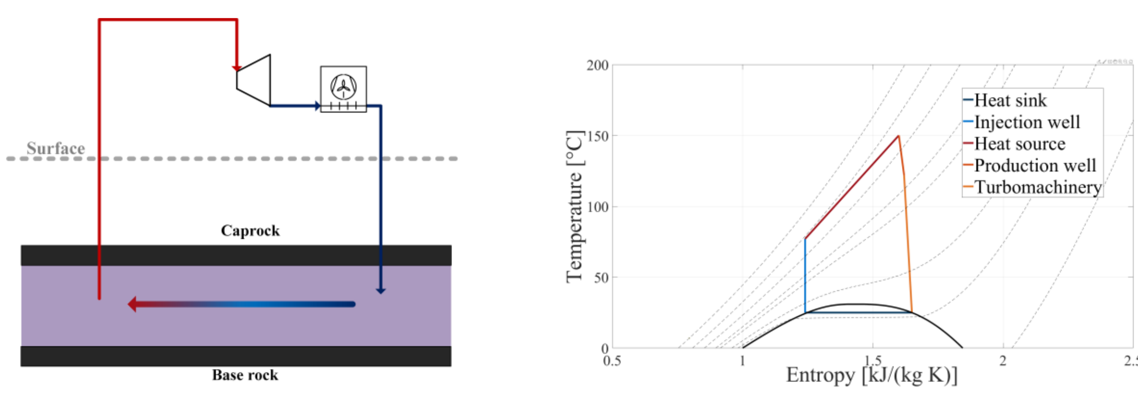
Only very few studies have investigated using $CO_2$ as a heat carrier in geothermal systems for CHP purposes. Gladysz et al. (2020) have investigated a $CO_2$-EGS system for CHP purposes and have recently published a follow-up study on the thermo-economic performance of such a system (Tagliaferri et al., 2022). A previous study by some of the authors of this work has investigated several CHP CPG configurations for different reservoir depths and district heating supply temperatures (Schifflechner et al., 2022). However, there has been no comparison between the required reservoir conditions for water and $CO_2$ supplying the same amount of heat to a district heating network. This work investigates the potential benefits and challenges of CPG systems for CHP applications, compared to geothermal systems using water/brine as the subsurface heat carrier. As such, this work contributes to an improved understanding of the potential role of CPG-CHP applications within the context of a future CCUS economy.

## 2. METHODS

The following section describes the general working principle of a CPG system and the considered CHP configurations, the system modeling and the assumed system parameters. Randolph and Saar (2011) and Adams et al. (2015) present a detailed description of the CPG concept.

### 2.1 General working principle of a CPG system and considered CHP configurations

The basic principle of the CPG system for sole power generation and the corresponding T-s diagram are visualized in Figure 1. Both the reservoir depth and the geothermal gradient determine the pressure and temperature at the inlet of the production well. Within the production well, both pressure and temperature of the $CO_2$ decrease. Since within the well $CO_2$ has gas-like properties, the enthalpy decrease mainly affects the temperature, while the pressure remains relatively high compared to a water system (more information on this effect is presented in Adams et al. (2015)). Thus, utilizing $CO_2$ as a heat carrier results in significantly higher wellhead pressures, being favorable for the direct power generation within a turbine. After the expansion in the turbine, the $CO_2$ is cooled down and (depending on the pressure level) condensed. This is necessary in order to ensure a sufficiently high density variation between the hot production and cold injection well, since this effect is pivotal as the driving force for the thermosiphon effect. As discussed in detail by Adams et al. (2014), who compared the achievable flow rates and power output due to the thermosiphon effect in geothermal systems considering both water and $CO_2$ as heat carriers**.** The strong thermosiphon effect is further enhanced by the low kinematic viscosity of $CO_2$ compared with water (Adams et al., 2014)**.** Thus, the CPG system can operate at a significantly higher mass flow rate without needing an additional pump or compressor equipment. Nevertheless, as discussed by Adams et al. (2015), the additional installation of a pump can substantially increase the achievable net power output of the CPG systems, especially for reservoirs with a depth of three kilometers or more.




(a) (b)

**Figure 1: (a) Simplified sketch of a CPG system and (b) the corresponding T,s-diagram for a thermosiphon system.**

This work compares two different CHP plant configurations, considering both a thermosiphon and a pumped CPG system. The simplified working principles of both CHP configurations are visualized in Figure 2. CHP Option I applies a simple serial concept. After the wellhead, the $CO_2$ flows through the district heating heat exchanger before entering the turbine. As an alternative, CHP Option II foresees the installation of the district heating heat exchanger on an intermediate pressure level. This configuration has initially been proposed by Gladysz et al. (2020) for a $sCO_2$-EGS system. The necessary outlet pressure of the first turbine stage is determined by the required district heating supply temperature and the pinch-point of the heat exchanger. After the $CO_2$ has passed through the heat exchanger it is expanded in a second turbine stage. The difference between both CHP options concerning the turbine expansion process is also shown in Figure 3. Even though Option II exhibits a considerably higher plant complexity, there are several reasons why it has the potential to achieve a significantly higher net output, which might justify the higher required installation costs and efforts. The theoretical favorability of this option can be explained by the behavior of the $CO_2$ isotherms in the p,h-diagram. As shown by Figure 4, the achievable power output from one kg of $CO_2$ in a turbine depends not only on the inlet and outlet pressure, but also on the inlet temperature. Considering the same in- and outlet pressure level for a $CO_2$ turbine, Figure 4 demonstrates that the inlet temperature strongly affects the achievable turbine power output. For example, only the small difference of 20 K between 110°C and 90°C turbine inlet temperature results in a power output reduction of 20 % in the case of a 90°C inlet temperature. Thus, if the $CO_2$ wellhead temperature is sufficiently higher than the required district heating supply temperature, it is favorable to use the $CO_2$ in the first high-pressure turbine stage.

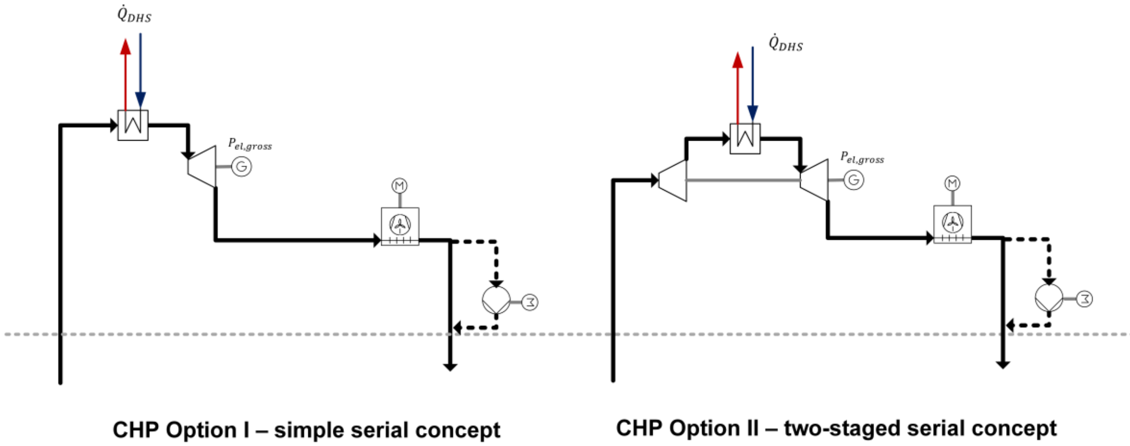



**Figure 2: Simplified plant layout of the considered CHP configurations.**

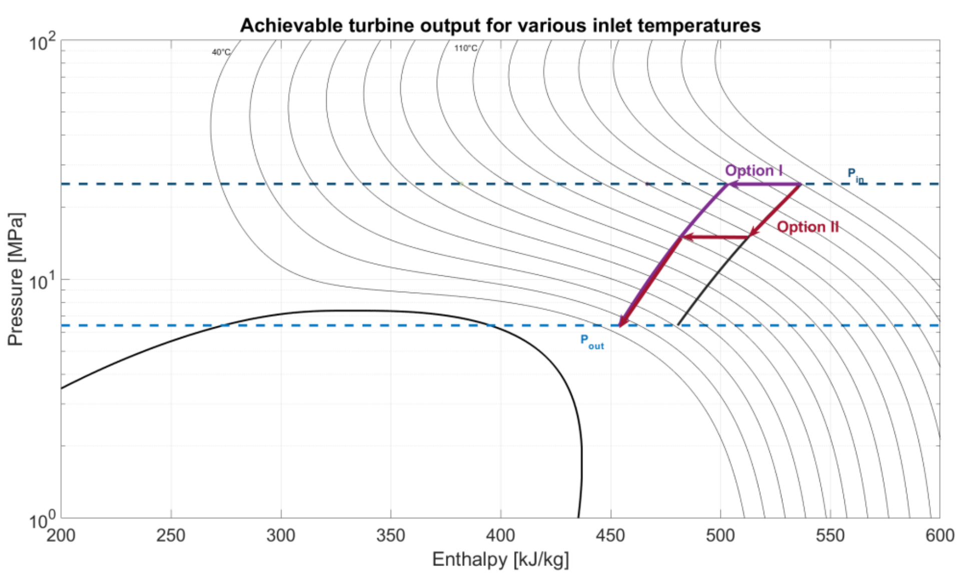



**Figure 3: Representation of the turbine expansion effect of both CHP options in the p,h-diagram.**

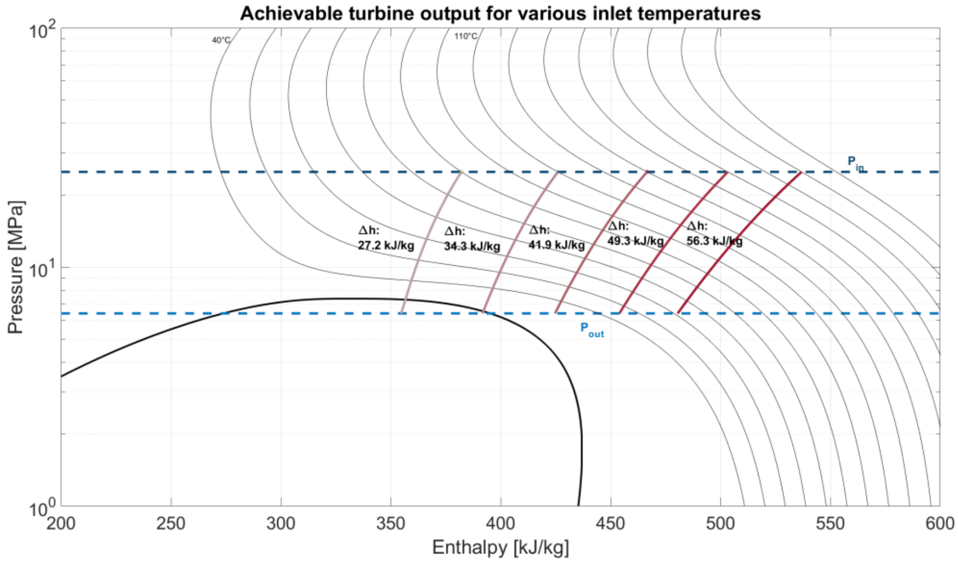



**Figure 4: Achievable mass-specific power output within the $CO_2$ turbine for the same inlet and outlet pressures but various turbine inlet temperatures.**

### 2.2 System modeling

In general, this work follows the modeling approach presented in detail by Adams et al. (2014) and Adams et al. (2015). Within both the production and injection well, the $CO_2$ and water properties are determined iteratively for length intervals of $\Delta z$ = 100 m. Furthermore, steady-state operation and no heat flow across the well boundaries are assumed. Subsequent formulas determine the pressure drop $\Delta P$ within one well segment due to changes in hydrostatic pressure and friction within the well. $\Delta P_{f,well}$ represents the pressure drop within one segment due to friction, f is the Darcy friction factor, $\Delta h$ is the change in the fluid enthalpy, V the fluid velocity and $\varepsilon$ the well roughness.

$$\Delta P = \rho g \Delta z - \Delta P_{f,well} \tag{1}$$

$$\Delta P_{f,well} = f \frac{\Delta z}{D} \frac{\rho V^2}{2} = f \frac{8 \, \dot{m}^2 \Delta z}{\pi^2 \rho D^5} \tag{2}$$

$$f = \left\{ -1.8 \log \left[ \frac{6.9}{Re} + \left( \frac{\varepsilon}{3.7 \, D} \right)^{1.11} \right] \right\}^{-2} \tag{3}$$

$$\Delta h = g \Delta z - \frac{\Delta(V^2)}{2} \tag{4}$$

More information about the whole system modeling approach can be found in a previous publication of some of the authors, which also discussed the validation of the CPG MATLAB model (Schifflechner et al., 2022).

### 2.3 System parameters and boundaries

Table 1 summarizes the main parameters and boundary values for the base scenario. A depth of 4.5 km is considered for the reservoir depth. Furthermore, a district heating demand of 15 $MW_{th}$ is considered, a typical value for existing geothermal CHP projects in Germany (Eyerer et al., 2020). Due to the significant temperature drop of the $CO_2$ within the production well, the required district heating supply temperature might significantly affect both the overall CPG performance and the required reservoir depth. The base scenario assumes a typical value of 80°C for a third generation district heating network (Gadd and Werner, 2014). However, a broader range is possible regarding the different generations of district heating systems and modern fourth generation networks might also operate with a supply temperature of 60°C (Lund et al., 2014). The effect of the required supply temperature on the required reservoir depth is discussed in Section 3.2. Further model parameters are taken from Adams et al. (2015) and Gladysz et al. (2020).

**Table 1: List of the main assumptions and boundary conditions**

| Parameter | Value |
|---|---|
| Depth | 4.5 km |
| Well diameter | 0.41 m |
| Well roughness | 55 µm |
| Permeability | $5 \times 10^{-14}$ m² |
| Reservoir length | 700 m |
| Reservoir thickness | 300 m |
| Geothermal gradient | 35 K/km |
| $T_{Res}$ | 172.5 °C |
| $P_{Res}$ | 45 MPa |
| Isentropic turbine efficiency | 0.78 |
| Minimal required vapor quality at the turbine outlet | 0.8 |
| Isentropic pump efficiency | 0.8 |
| Heat demand | 15 $MW_{th}$ |
| DHS return and supply temp. | 50 – 80 °C |
| Pinch-Point temp. condenser | 3 K |
| Ambient air temperature | 15 °C |
| Electricity demand of the fans | 0.15 kW per kg $s^{-1}$ of air flow |

## 3. RESULTS

### 3.1 Comparing the different CPG CHP options

Figure 5 visualizes the achievable net power output for the investigated CHP concepts considering a reservoir depth of 4.5 km and a required district heating network supply temperature of 80°C. The results are presented for both a sole thermosiphon and a pumped system. The application of a CHP system reduced the achievable net power output due to the effect on the achievable turbine output, as discussed previously in Figure 4. While for a thermosiphon system the power reduction is only around 11 %, a significantly higher net power output decrease of around 32 % can be observed for a pumped system. Comparing both investigated CHP options demonstrates the favorability of CHP Option II for both systems. Thus, despite the higher plant complexity, this option can result in significantly higher power outputs and achievable revenues. However, in order to successfully apply the CHP option II, a wellhead temperature is required at least 15 – 20 K above the demanded district heating supply temperature. Thus, it is only applicable for rather deep reservoirs, while CHP Option I would be chosen for CPG systems with lower wellhead temperatures.

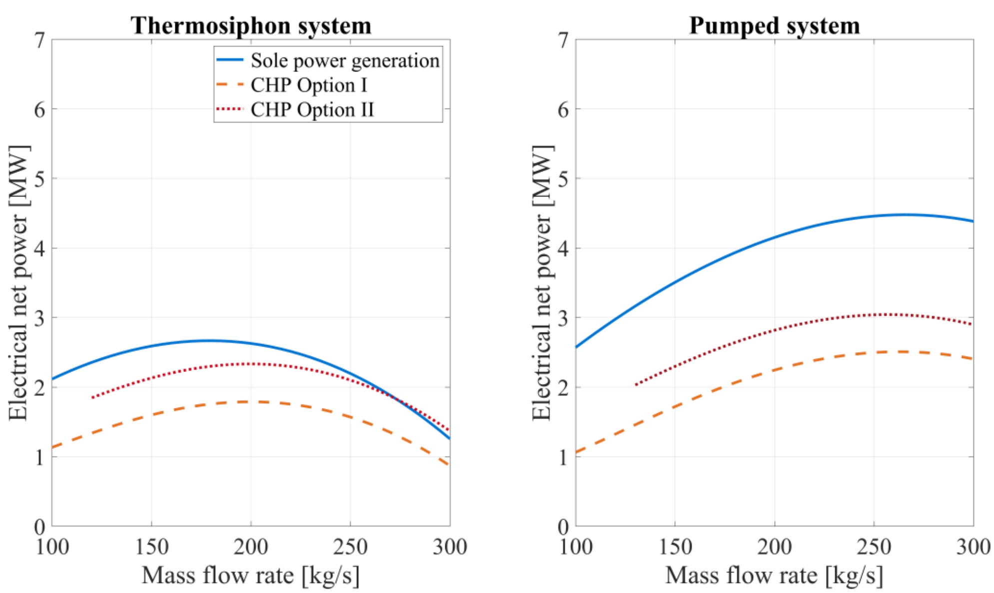



**Figure 5: Achievable net power output for a thermosiphon system and a pumped system**

### 3.2 Required reservoir depth and geothermal gradient for different DHS demand characteristics

The results in Figure 6 display the required reservoir depths for both water and $CO_2$ in order to be able to provide the required district heating systems supply temperature. As expected, $CO_2$ systems require higher reservoir depths due to the lower achievable wellhead temperatures for the same reservoir conditions (cf. Section 2). Depending on the geothermal gradient, the required district heating system supply temperature and the amount of required heat supply, the necessary CPG reservoir depth is between 800 and 1100 m higher than in the case of a geothermal system utilizing water as heat carrier fluid. Furthermore, it can be seen that for $CO_2$ the amount of required heat supply has a strong effect on the required reservoir depths, while it has no impact on the water systems. In order to be able to supply 20 $MW_{th}$ instead of 10 $MW_{th}$ requires up to 300 m higher reservoir depths. Higher geothermal gradients and/or lower district heating system supply temperatures decrease the difference between the required reservoir depths.

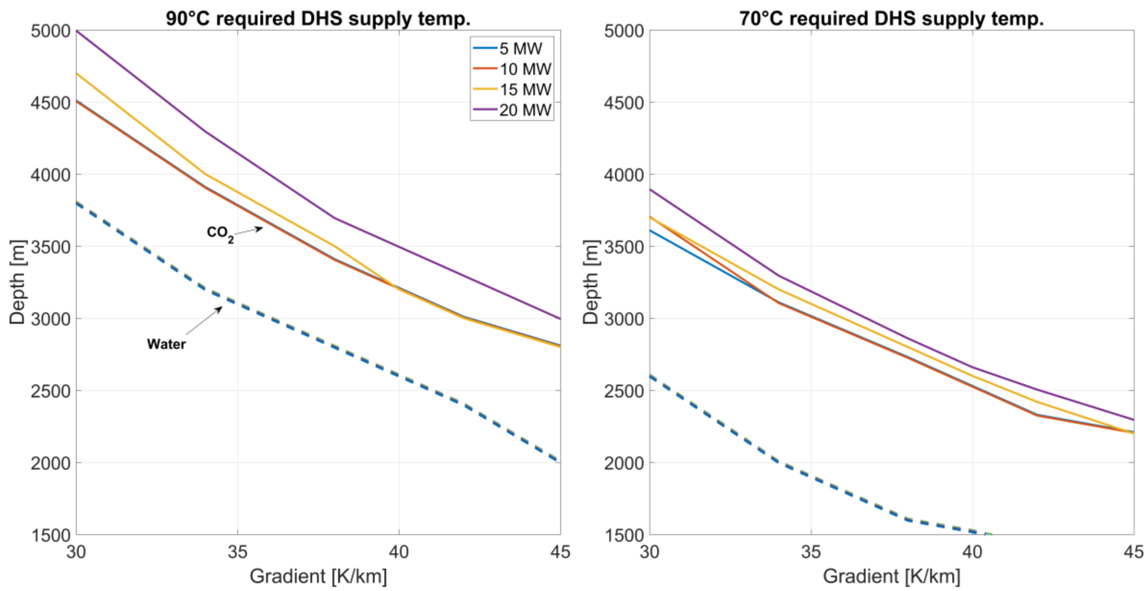



**Figure 6: Required reservoir depth to supply the heat demand at a specific required district heating system (DHS) supply temperature level for $CO_2$ (solid line) and water (dashed line).**

## 4. CONCLUSION & OUTLOOK

In recent years, there has been an increasing interest CPG system, which is an attractive approach to combine CCS with geothermal energy production. Applying $CO_2$ as the heat carrier fluid can be more efficient than water since it displays higher mobility and its higher thermal expansion coefficient results in a strong thermosiphon effect. While CPG systems are highly attractive for sole electric power generation in former oil and gas fields, the application in regions with higher population densities is also possible. In order to increase public acceptance and support the decarbonization of the heating sector, CHP CPG systems might be an attractive concept for selected CPG sites. Due to the gas-like behavior of $CO_2$ in the production well, CPG systems require higher depths compared to water in order to provide the same temperature level for the district heating network. Thus, CPG systems might not be the first choice for sole heating projects. However, in the case of a promising CPG site e.g. close to a smaller town or industry process, it should be considered to supply also the local heating by the CPG in order to increase the local acceptance and decarbonize the heating sector.

Two different CPG CHP configurations are evaluated within this work for a reference case with a depth of 4.5 km and a required district heating network supply temperature of 80°C. The application of a CHP system reduced the achievable net power output due to the effect on the achievable turbine output as discussed previously in Figure 4. While for a thermosiphon system the power reduction is only around 11 %, a significantly higher net power output decrease of around 32 % can be observed for a pumped system. Comparing both investigated CHP options demonstrates the favorability of CHP Option II (heat extraction on an intermediated pressure level) for both systems. Thus, despite the higher plant complexity, this option can result in significantly higher power outputs and achievable revenues. However, it is only applicable for rather deep reservoirs, while CHP Option I would be chosen for CPG systems with lower wellhead temperatures. Furthermore, the required reservoir depths for both water and $CO_2$ are evaluated with respect to different district heating supply temperatures and heat demand as well as geothermal gradients. Depending on the assumed boundary conditions, a CPG system requires a higher reservoir depth between 800 and 1100 m. Thus, CPG CHP can only be applied to locations with promising geological settings in a sufficient depth. If these conditions can be met at a site, CPG CHP systems can still to provide a higher total energy output than a traditional geothermal system with water as heat carrier. In order to assess this difference, further wholistic studies comparing water and $CO_2$ as heat carrier for CHP applications are necessary, also considering the effect of part-load effects due to the varying district heating demand (Schifflechner et al., 2020). Especially the effect of dissolved water in the $CO_2$ production well can significantly increase the CHP potential of CPG systems due to the significant increase in the wellhead temperature (cf. Fleming et al. (2020)). Thus, considering the potential natural presence of water within the CPG system could strongly increase the CHP potential and shall be further studied in a holistic numerical system study.

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