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Annual Performance Profiles of CO_2-Plume Geothermal (CPG) Systems: Impact of the Ambient Conditions

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ABSTRACT

The CO_2-Plume Geothermal (CPG) technology is a promising concept within the context of a future CCUS economy and enables combining carbon sequestration with power generation. Various regions worldwide display promising geological settings for future CPG projects. However, next to the geological characteristic, also the ambient temperature has a pivotal impact on the CPG performance and potential off-design performance of its components. This work investigates the annual net power output for three promising regions regarding potential future CPG systems: Switzerland, Saudi Arabia and Texas, United States. The results show that Switzerland displays the highest net power output for all months, followed by Texas. For both Texas and Saudi Arabia, the achievable net power is only marginal during the hottest summer months. However, also in Switzerland the CPG system displays a significantly lower net power output during the summer. Nevertheless, the significant power output potential of the CPG technology during colder periods is promising, considering the current and future installed capacities of PV in the electricity mix. Thus, CPG can especially provide high power outputs during periods with low or no PV power supply. In combination with advanced CPG systems for enhanced flexibility, CPG has the potential to provide reliable flexibility in combination with its general advantages of a true CCUS technology.

INTRODUCTION

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 using CO_2 as an energy carrier in geothermal energy systems. This refers to both closed-loop systems using CO_2 [1], but also to so-called CO_2-Plume Geothermal (CPG) [2], which combines CCS with geothermal, using CO_2 instead of water as a subsurface heat and pressure energy carrier. CO_2 as a subsurface working fluid is more efficient as it has a

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higher mobility (inverse kinematic viscosity) and its large thermal expansion coefficient results in a thermosiphon effect that reduces the pumping power required [3]. CO_2 can also be directly 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 both CO_2 Capture Utilization and Storage (i.e. CCUS) [2]. In recent years, CPG has experienced increasing interest from academia and industry. Several in-depth studies have assessed the impact of various parameters such as the geothermal gradient, wellbore diameter or reservoir permeability on the CPG performance (e.g. [3,4]). However, these studies have not evaluated the potentially significant impact of the varying ambient conditions on the CPG performance profile. The potential effect of the air temperature on the CPG performance has only been discussed in a paper by Adams and Kuehn (2012) [5] and in a more recent work by van Brummen et al. (2022) [6], but no comparison for different potential site locations has been carried out. Furthermore, the effect of the changing ambient temperature on the turbine and compressor performance due to variations in the mass flow rate and operating pressures was neglected, which might be a crucial over-simplification considering the potential performance degradation due to part-load effects [7,8]. Also, Nielson et al. (2022) [9] highlight the strong impact of the CO_2 injection conditions on the thermo-economic performance of a CO_2 thermosiphon geothermal system. Nevertheless, the impact of the ambient conditions and cooling technology on the annual CPG performance profile and detailed equipment design has not been evaluated in detail so far [10]. Thus, this contribution assesses and discusses how the CPG performance profile might vary across several geographical settings and evaluates the impact of the cooling technology. Therefore, valuable insights regarding the most attractive settings for future CPG systems can be drawn.

FUNDAMENTALS AND METHOD

Working principle of CPG

The basic working principle of the CPG technology is visualized in Figure 1. Similar to a standard CCS project, CO_2 is injected in a naturally permeable reservoir. The geothermally heated CO_2 is then back-produced, expanded through a turbine, cooled, and re-injected into the reservoir so that all CO_2 is ultimately permanently stored underground [2]. The main advantage of using CO_2 instead of water is its favorable mobility (the inverse of kinematic viscosity), which enables higher mass flows through the reservoir. This mobility effect also dominates over the reduced specific heat capacity of sCO_2 compared to H_2O within the reservoir. Thus, the use of CO_2 increases 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 [11]. Another benefit of using CO_2 is the thermosiphon effect [3], 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. While the general working concept requires no pumping power due to the strong thermosiphon effect (cf. [3]), several studies (cf. [12–14]) demonstrate that the additional installation of a compressor can further increase the achievable net power output of a CPG system. Next to pivotal system parameters such as reservoir depth, permeability and well diameter (cf. [12]), also the CO_2 injection temperature has a strong impact on the achievable system performance (cf. [6,9,15]) and the potential part-load performance of the system's component.

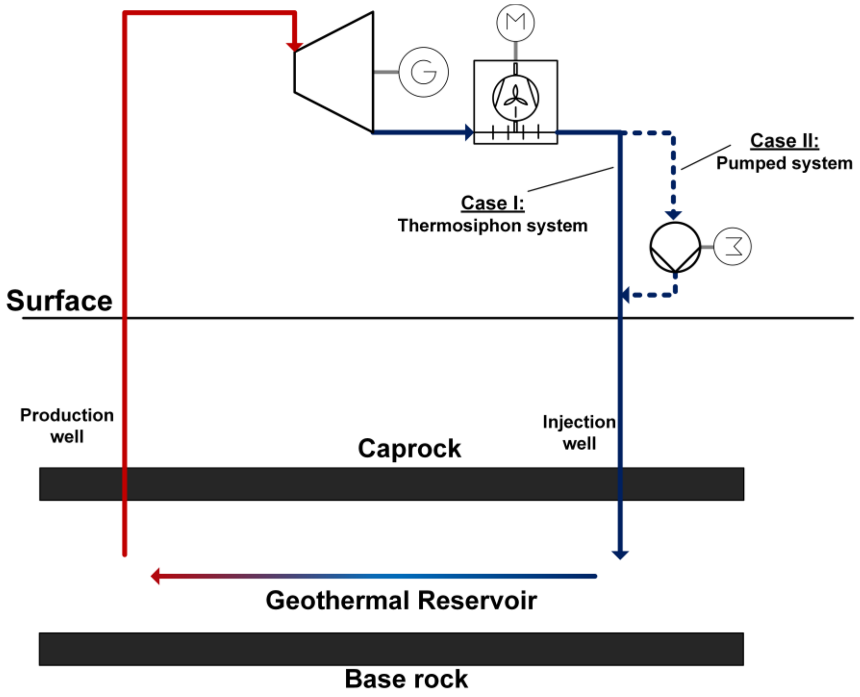
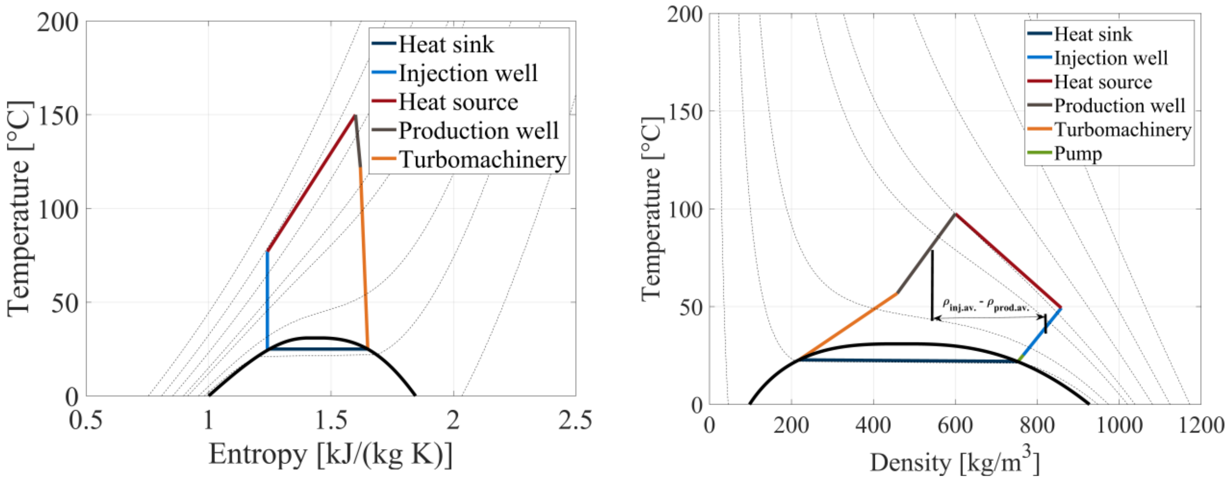


Figure 1: General working principle of a CPG system



(a)

(b)

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

Modelling of the CPG system and its main components

The CPG system is modelled in MATLAB and REFPROP by using a model which is described in a previous publication of some of the authors [14]. The general working principle follows the detailed description by Adams et al. [3] and also used in ETH's open-source code genGeo [4]. Within the wells, the property changes of the CO_2 are calculated iteratively for length intervals of

Δz = 50 m. Furthermore, steady-state operation and a lack of heat flow across the well boundaries are assumed [16]. The subsequent formulas determine the pressure drop ΔP within one well segment due to change 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, Δh is the change in the fluid enthalpy, V the fluid velocity and ε the well roughness.

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

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

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

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

Darcy’s law for a steady, laminar 1D flow through a porous medium calculates the pressure drop within the reservoir [12]. Also here, a length interval ΔL of 50 m is considered.

$$\Delta P_{res} = \left[\frac{\mu \, \Delta L}{\rho_i \, A_{res}} \right] \frac{\dot{m}}{\kappa_{res}} \tag{6}$$

The electrical net power $P_{el,net}$ for the thermosiphon and pumped system are calculated using the following two equations:

$$P_{el,net,thermo} = P_{el,turb} - P_{el,fans} \tag{8}$$

$$P_{el,net,pump} = P_{el,tur} - P_{el,fans} - P_{el,pump} \tag{9}$$

Detailed off-design models are integrated into the model, incorporating the off-design performance assessment of the compressor, turbine, and heat exchanger. Due to space limitations, only the procedure for the CO_2 compressor is presented in detail, while for the off-design models for the turbine and heat exchanger, more information can be found in Dawo et al. 2019 [17] and Manente et al. (2017) [18] respectively. Regarding the turbo compressor, in the first step, a two-zone model is applied [19]. Inlet pressure, inlet temperature, outlet pressure and mass flow rate are specified as the boundary conditions. In an iterative process, the design tool computes the blade angles, diameters and width of the flow channel together with a 3D impeller model. The geometric information is then fed into a mean-line compressor model [20]. This model solves the continuity equation, 1st law of thermodynamics and Euler work equation together with different loss models to generate the performance map for different inlet temperatures/pressures and mass flow rates. The program has been validated against measurements of the sCO_2-HeRo compressor [21]. Subsequent figure displays exemplary a resulting performance map for the CO_2 compressor, which is then integrated into the simulation model.

The following simulations are carried out for a reservoir depth of 2.5 km and the same reference parameters as by Hansper et al. (2019) [13] for one five-spot configuration (meaning one injection and four production wells).

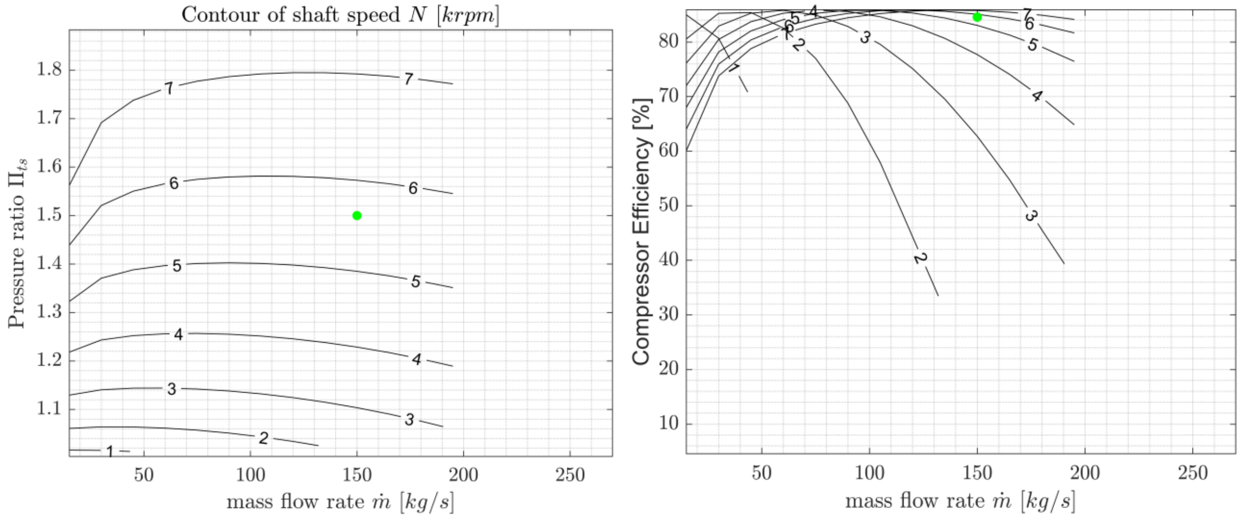


Figure 3: Contour plot of the shaft speed depending on the pressure ratio and mass flow rate (left) and of the efficiency depending on the shaft speed and mass flow rate (right). The green dot represents the design point.

The investigated case study regions

In order to study the effect of the different ambient temperatures on the annual performance output, three different promising case study regions are evaluated. They are chosen based on their favorability for potential CPG projects and significant variations in their daily and annual ambient temperature profiles. The three study regions are:

Switzerland: Hau et al. (2021) [22] present a detailed case study for the Western part of the Swiss Molasse Basin as a promising region for CPG, especially when e.g. CO_2 from a local large-scale CO2 capture source such as a cement plant is used.

Saudi-Arabia: The Arabian Plate has promising characteristics for CPG systems [23], potentially also in combination with future hydrogen generation [24].

Texas, USA: Maldonado et al. (2021) [25] evaluate several promising regions within the United States for CPG systems, among others in Western Texas.

The subsequent figure displays the different ambient temperature profiles for these three regions. The weather data are imported from the typical metrological year database from the open-data Photovoltaic Geographical Information System (PVGIS) platform. While Switzerland displays a rather frequent appearance of hours with ambient temperature below 10°C, Saudi Arabia has only very few hours below this value and a high number of hours with temperatures above 30°C.

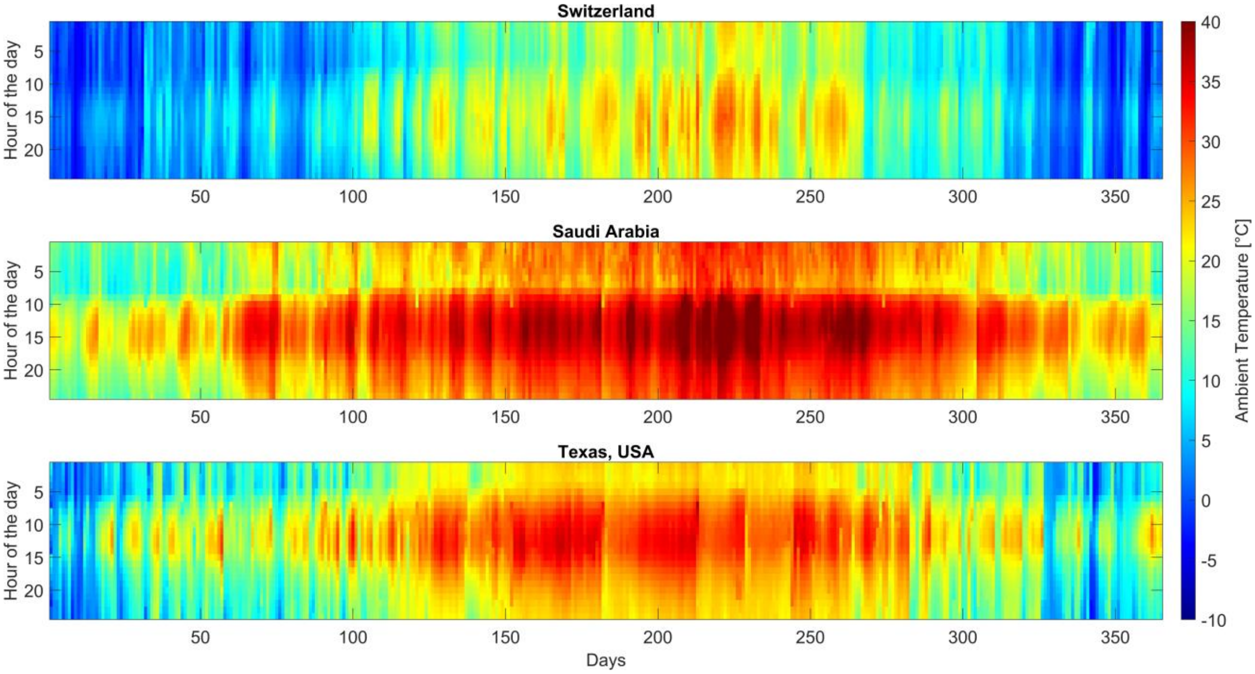


Figure 4: Hot map of the hourly ambient temperatures of the three different case study regions.

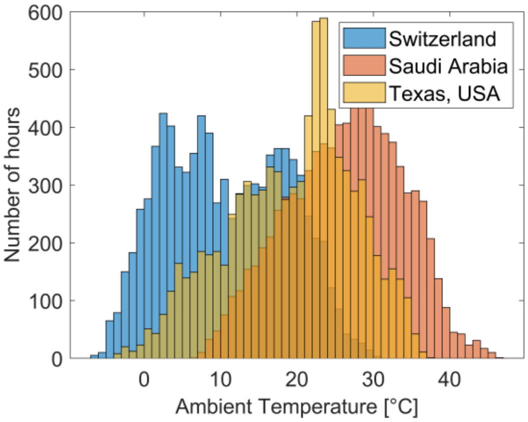


Figure 5: Histogram of the occurring number of hours with the corresponding ambient temperature for the three different case study regions.

RESULTS AND DISCUSSION

The following section presents the obtained results for both a thermosiphon CPG and a pumped CPG system considering the three different case study regions. First, subsequent figure visualizes the general achievable power output of both CPG systems as a function of the ambient temperature. As it can be seen, the achievable net power output strongly correlates with the ambient temperatures. While cold temperatures might significantly increase the achievable power output, for temperatures above 20°C, the archivable net power drops strongly. The presented general relationship between the achievable net power output and the ambient temperature combined with the previously presented off-design models is now used to evaluate the annual net power output for three case study regions.

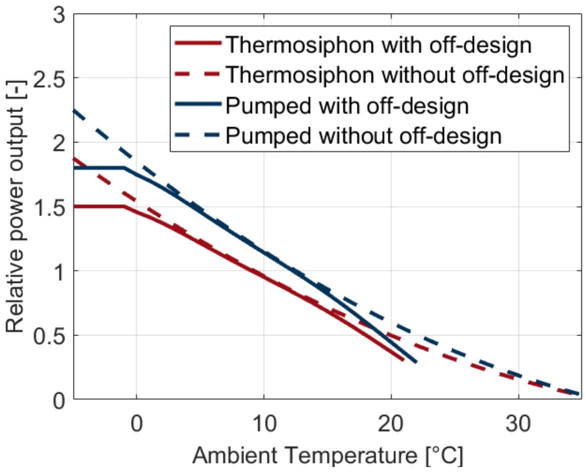


Figure 6: Relative power output of a thermosiphon and pumped system as a function of the ambient temperature with the reference point at 9°C.

Since all three case study regions are simulated for the same reservoir conditions, their nominal power output at the reference point of 9°C is the same and corresponds to 3.4 MW_{el}. By combining the annual ambient temperature data and the off-design simulation model, the annual achievable net power output for all three regions is determined. Subsequent figure visualizes the different net power output for all three regions on a monthly basis. The results show that Switzerland displays the highest net power output for all months, followed by Texas. For both Texas and Saudi Arabia, the achievable net power is only marginal during the hottest summer months. However, also in Switzerland the CPG system displays a significantly lower net power output during the summer time.

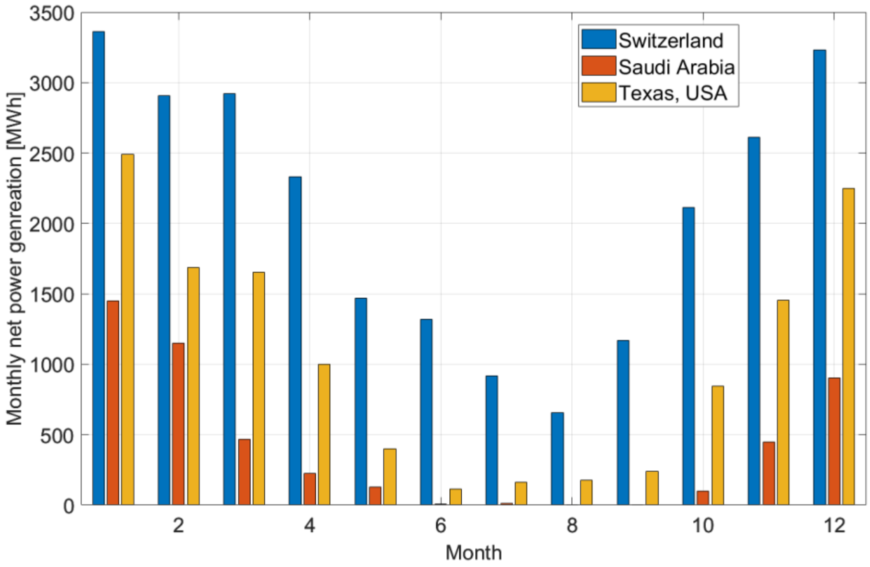


Figure 7: Monthly generated net power output for the three different case study regions.

CONCLUSION

The CPG technology is a promising concept within the context of a future CCUS economy and enables the combination of carbon storage with power generation. Various regions worldwide display promising geological settings for future CPG projects. However, next to the geological characteristic, also the ambient temperature has a pivotal impact on the CPG performance and potential off-design performance of its components. This work investigates the annual net power output for three promising regions regarding potential future CPG systems: Switzerland, Saudi Arabia and Texas, United States. The results show that Switzerland displays the highest net power output for all months, followed by Texas. For both Texas and Saudi Arabia, the achievable net power is only marginal during the hottest summer months. However, also in Switzerland the CPG system displays a significantly lower net power output during the summer. Nevertheless, the significant power output potential of the CPG technology during colder periods is promising, considering the current and future installed capacities of PV in the electricity mix. Thus, CPG can especially provide high power outputs during periods with low or no PV power supply. In combination with advanced CPG systems for enhanced flexibility (cf. van Brummen [6]), CPG has the potential to provide reliable flexibility in combination with its general advantages of a true CCUS technology.

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