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Assessment of performance and costs of CO2 based Next Level Geothermal Power (NLGP) systems

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ABSTRACT

Alternative power cycles based on supercritical carbon dioxide (sCO_2) are increasingly gaining in importance of scientific and industrial research in the energy sector. The applications for which this new technology is being discussed are mainly in the area of direct heated applications such as coal fired, concentrated solar power and indirect heated applications such as waste heat recovery and combined cycle power plants. Geothermal power generation based on supercritical carbon dioxide (sCO_2) is a topic of geophysical research and has been the object of numerous studies over the past years. In comparison to conventional hydrothermal power plants, such CO_2 based next level geothermal plume power plants (NLGP) systems exhibit several thermophysical advantages. Essentially, a more effective geothermal heat extraction and less need for auxiliary pumping power, due to a much stronger thermosiphon effect, compared to water-based geothermal energy extraction can be highlighted. In this paper a thermodynamic and energy conversion evaluation of NLGP systems is provided. The results are compared to conventional hydrothermal power cycles. The results of the thermodynamic calculations show that NLGP systems can supply significantly more electricity, compared to hydrothermal systems, particularly at “shallow" depths of 2-3 km and at low reservoir permeabilities. Based on the thermodynamic simulation calculations, initial turbine design considerations are discussed. Initial blade path calculations show a compact turbine layout for the CO_2 turbine. However, compared to fossil application the near critical expansion of a geothermal power plant leads to different design requirements. Initial cost estimations show that NLGP systems can generate electricity at competitive levelized costs of electricity (LCOE) at much lower resource temperatures than hydrothermal systems, thereby considerably expanding the geothermal resource base worldwide.

INTRODUCTION

Unlike to other renewable energies such as wind and solar energy, geothermal energy is available all year round and with virtually no fluctuations. The associated controllable and demand-oriented feed-in possibility is a great advantage of geothermal power plants. On the other hand, only a few regions on earth can be considered as locations for conventional geothermal power generation due to the required geological boundary conditions. Low temperature levels of the reservoirs that can be tapped at shallow depth prevent global economic use. Temperatures of around 100 °C make geothermal power generation using conventional methods based on a secondary Clausius Rankine or Organic Rankine cycle (ORC) unprofitable.

Against this background, the use of supercritical carbon dioxide (sCO_2) as an alternative energy-extraction medium from naturally permeable sedimentary-basin reservoirs and the use in direct and indirect geothermal power plant applications has been discussed in several publications. [1, 2, 3, 4]

The basic concept of a NLGP system, which is shown in Figure 1, can be outlined as follows: Waste CO_2 from one or several fossil fuel power plants, or other CO_2 emitters, is captured using Carbon Capture (CC) technologies. The captured CO_2 can be transported, for example through pipelines, to a NLGP site, where the CO_2 is injected into a geological CO_2 storage formation. In order to ensure economical operation of the CO_2 system, a high temperature of the CO_2 storage formation must be maintained, i.e. at least about 100°C. These geologic formations or reservoirs also need to have sufficient permeability of >10 mD (1 mD = 10^{-15} m^2) and need to be overlain by a caprock of sufficiently low permeability of about <0.01 mD to enable efficient CO_2 injectivity into the reservoir through the injection well and to prevent CO_2 flow through the caprock, against which the CO_2 pools upwardly. In the reservoir, the CO_2 is geothermally heated and a portion is piped back to the surface power plant, where it

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is expanded in a turbine, driving a generator, and hence producing electricity.

The temperature-dependent density variation of sCO_2 is large compared to water. In addition, supercritical CO_2 has a kinematic viscosity that is, under base-case NLGP conditions [1, 2, 3] of a reservoir at a depth of 2.5 km, under hydrostatic fluid pressure and a temperature of 100°C, about 25% the kinematic viscosity of water. In other words, under these conditions the mobility of sCO_2 is four times higher than that of water. Furthermore, the thermal expansibility of sCO_2 is much larger than that of water. The low kinematic viscosity and high thermal expansion coefficient of sCO_2 result in the formation of a strong thermosiphon, a physical effect which circulates a fluid without the necessity of a mechanical pump. Driven by this thermosiphon a Brayton cycle can be established, generating electricity, eliminating this particular parasitic power requirement of water-based geothermal systems.

In this paper a first technical and economic assessment of CO_2 based geothermal power plants is given. Initial performance calculations are presented and basic design considerations such as turbine design are carried out. The results are compared with conventional hydrothermal power plants (brine/ORC). Furthermore, an initial economic evaluation is presented based on LCOE calculations.

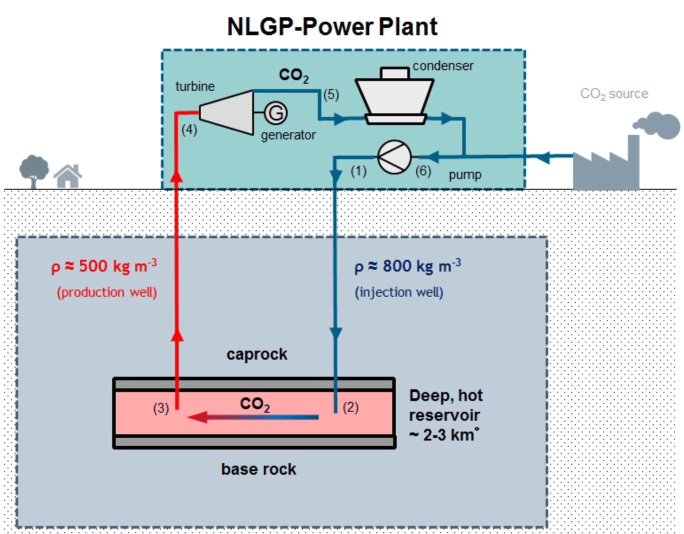

Figure 1: Exemplary illustration of a geothermal power cycle based on CO_2.

SIMULATION AND MODELING

The thermodynamic cycle simulations were carried out by an in-house simulation software and MS-Excel. Initial sCO_2 / ORC turbine design calculations were performed with internal design tools. The thermodynamic properties of CO_2, water and the ORC media were provided by the REFPROP (REFerence fluid PROPerties) data base developed by the National Institute of Standards and Technology. [5]

The layout of a NLGP system according to figure 1 is comparatively simple. The related thermodynamic changes in the state of the CO_2 cycle are shown in the T-s diagram in figure 2. The power plant essentially consists of three main components:

- turbine (condition 4 to 5)
- condenser (5 to 6)
- optional pump (6 to 1)

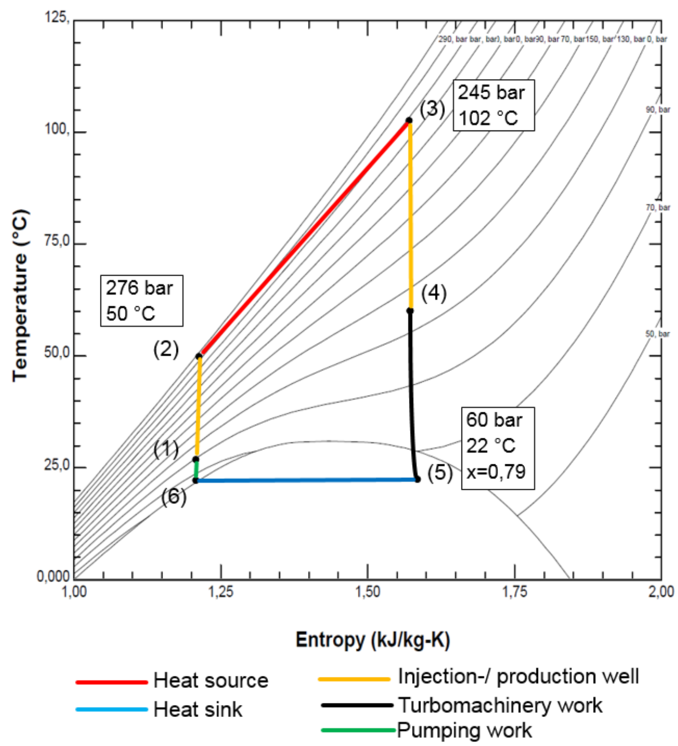

Figure 2: Exemplary illustration of a geothermal power cycle based on CO_2.

The CO_2 is injected into the subsurface in supercooled state (1). With increasing depth and thus increasing hydrostatic pressure, the temperature and pressure level increase until the CO_2 reaches supercritical state (2). The flow in the injection well is modeled as a vertical pipe considering the hydrostatic pressure according to equations 1 to 3. Based on the first law of thermodynamics and Bernoullie, the geodetic height difference z, the acceleration due to gravity g and the enthalpy of fluid h are used to determine the pressure change in the borehole. In addition, ζ represents the pressure loss coefficient and c the flow velocity of the fluid. Because the fluid density is pressure-dependent, an integration over the drilling length is necessary. For this purpose, the borehole is divided into 200 or rather 100 m long sub-segments where subscripts i and $i+1$ mark the beginning and the end of each element. The fluid density is considered to be constant within a segment.

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(1) $$\int_{i}^{i+1} \frac{dp}{\rho} = g \cdot z_{i,i+1} = h_{i+1} - h_i$$

(2) $$\Delta p_{i,i+1} = g \cdot z_{i,i+1} \cdot \rho_i - \Delta p$$

(3) $$\Delta p = \zeta \cdot \frac{\rho}{2} \cdot c^2$$

After compression in the injection well, the supercritical CO_2 is geothermal heated to reservoir temperature. The flow in the geologic reservoir is characterized by Darcy's law [2]. It combines the flow properties of a fluid with the properties of a porous medium and enables the calculation of a (fictitious) flow velocity in the reservoir in equation 4. Therefore, κ describes the permeability of the rock formation, μ the dynamic viscosity of the fluid, Δp_{Res} the pressure loss in the reservoir and L_{Res} the corresponding flow length. Assuming a constant mass flow, the pressure loss in the reservoir is thus determined by the geothermal mass flow $\dot{m}_{geo}$ and the flow cross-section A_{Res} in the reservoir according to equation 5.

(4) $$c_{Res} = \frac{\kappa}{\mu} \cdot \frac{\Delta p_{Res}}{L_{Res}}$$

(5) $$\Delta p_{Res} = \frac{\mu}{\rho} \cdot \frac{L_{Res}}{A_{Res}} \cdot \frac{1}{\kappa} \cdot \dot{m}_{geo}$$

As fixed boundary conditions for the process simulation the reservoir temperature and hydrostatic pressure are defined at the bottom of the production well in state (3). Afterwards, the heated CO_2 flows through the production well to the surface, where it is used to generate electricity. The supercritical CO_2 expands in the turbine into the two-phase state region (5), is cooled in the condenser and converts to liquid state (6). Above-ground pumping, to state (1), enables a larger geothermal mass flow and thus increases the power plant output. Due to the so-called thermosiphon effect, which is induced by the variable density of CO_2, it is also possible to operate the system without additional pumps.

The storage formations suitable for NLGP systems are much larger than those used for conventional hydrothermal geothermal plants. Due to their size, systems with several production wells are possible, which increases the thermal output of the reservoir. The coordination number *N* determines the number of production wells. The coordination number *N =1* describes a 5-point system with an edge length of one kilometer consisting of one injection well and four production wells. The above-ground power plant is located centrally in the immediate vicinity of the injection well.

With an increased coordination number, the edge length and thus the number of injection and production wells increases in the manner shown in figure 3. This makes the system scalable. The system size should be chosen depending on the boundary conditions of the reservoir and the economic efficiency.

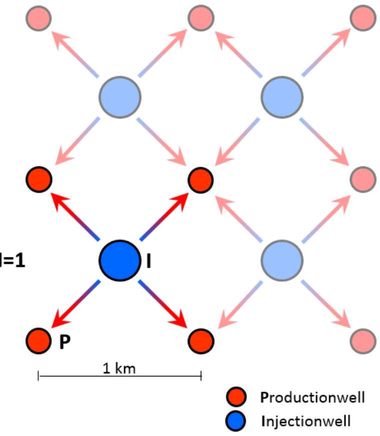

Figure 3: Hole pattern in relation to the coordination number N

THERMODYNAMIC EVALUATION

The cycle layout and reference conditions for the thermodynamic evaluation were chosen in accordance to Adams et al. [2] for a single 5-spot well pattern (N=1). The "base case" conditions, reflecting typical geologic reservoirs, are summarized in table 1. In opposite to Adams et al. [2] where R245fa was used as ORC-fluid medium, isobutane is used as the ORC-fluid medium in the presented investigation because of its lower environmental impact, lower costs, and as it is a common fluid in the considered temperature range.

Figure 4 summarizes the results of the thermodynamic analysis performed. The cumulative column represents the turbine power. Under reference conditions according to table 1 NLGP systems achieve a significant larger net power output (blue bars) compared to conventional, brine based (indirect) power plants.

Table 1: Summary of NLGP base case conditions

	NLGP Base Case
Coordination number N [-]	1(1km x1km)
Depth [m]	2500
Permeability [mD]	50
Temperature gradient [°C/km]	35
Well diameter [m]	0.41
Cooling Type	Wet Cooling tower
Heat Sink Temperature [°C]	15
Approach Temperature [°C]	7

The key factor for this result is the strong thermosiphon effect and lower pressure losses of the reservoir flow caused by the lower kinematic viscosity of sCO_2. On one hand the 4-times higher mobility of sCO_2, compared to water, leads to an approximate quadruplication of the CO_2 mass flowrate through

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the turbine. On the other hand, the specific heat capacity

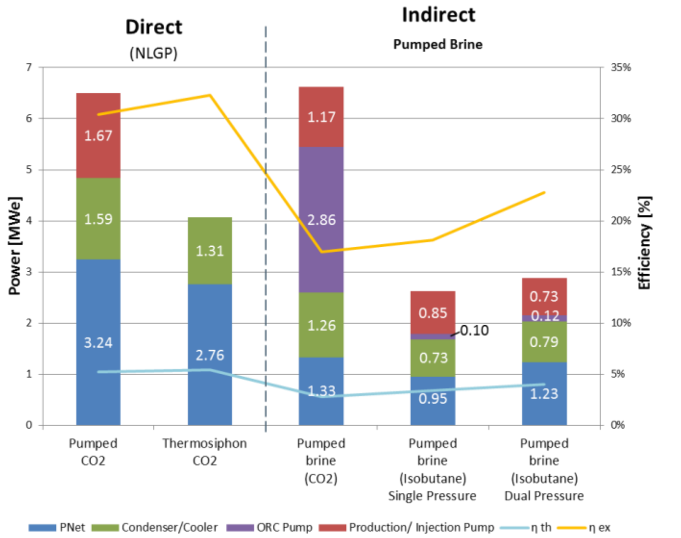

Figure 4: Comparison of the power output for different geothermal concepts (i.e. NLGP and indirect brine) at base case conditions.

of sCO_2 is approximately half, so that the transferred heat and thus the resulting net electric power output of the NLGP power plant, is approximate 2-3 times larger compared to conventional water-based (indirect) geothermal power plants. In addition, the direct conversion of the thermal energy in the turbine eliminates the exergy losses in a heat exchanger, so that the exergetic efficiency is higher than that of the indirect systems. In indirect systems, the isobutane-driven cycles achieve a higher net output. This can be explained by the high parasitic power losses in the secondary cycle when a gas, such as CO_2, is compressed. By installing a dual-pressure ORC process, the efficiency of the brine case can be increased, which is also shown in figure 4. In this case, the geothermal heat is transferred at two different pressure levels to the working medium, which reduces the temperature differences between the fluids and thus the exergy losses in the heat exchanger. A larger amount of heat is thus extracted from the geothermal medium, which improves the thermal efficiency and decreases the reinjection temperature. The amount of heat absorbed in the reservoir is therefore correspondingly larger. Moreover, installing a dual-pressure process raises the complexity of the system. However, the efficiency and the net power output are still below the results of the NLGP cycle. In conclusion, the present thermodynamic analysis supports the results of Adam et al. [2].

Since geothermal power generation depends on the conditions of specific geological formation in the reservoirs the impact of reservoir depth and permeability was calculated in a next step which is outlined in four different combinations in figure 5.

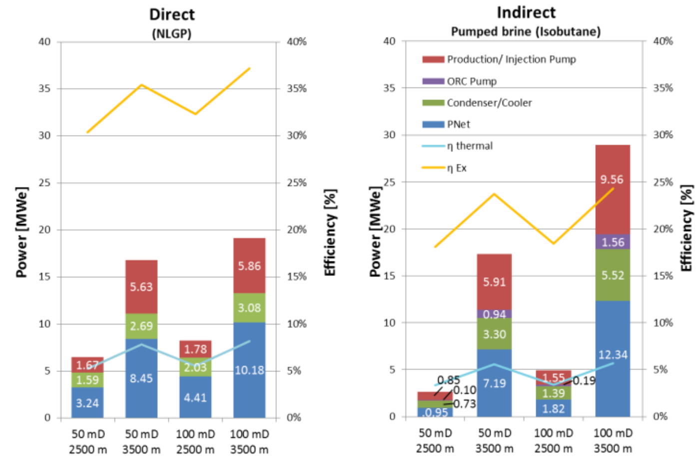

Figure 5: Illustration of the impact of different geologic conditions, (i.e. reservoir permeability and depth) on electric power output.

With increasing depth, the storage temperature and thus the temperature of the extracted geothermal fluid rise due to the geothermal temperature gradient. In both cycle types the turbine inlet temperature increases and thus the turbine power output. In addition, in the NLGP system, the higher reservoir temperature causes a larger difference in the average density between the injection and production wells, thereby enhancing the thermosiphon effect. Conversely, in the indirect cycle an increased reservoir temperature has an influence on the flow behaviour of the brine and thus on the pressure losses in the reservoir flow. The lower the dynamic viscosity of the geothermal medium, the lower the pressure losses in the reservoir flow. In contrast to the dynamic viscosity of CO_2, that of brine is strongly dependent on the temperature. With increasing reservoir depth and temperature the dynamic viscosity of the brine decreases significantly. As a result, the pressure losses in the reservoir and thus the required pumping capacity of the geothermal pump decrease. This enables the extraction of a larger brine mass flow and thus larger component outputs. Overall, the increase in efficiency due to an increased reservoir depth can substantially be explained by the temperature elevation in the reservoir and its influence on the flow behavior of the brine. At increased permeability (with the same depth) the pressure losses in the reservoir, which need to be compensated, are lower. This results in a lower required pumping capacity and thus a higher net power output.
For larger drilling depths and simultaneously enhanced permeability, the increase in performance is correspondingly greater.

In figure 6 the exergy transferred in the reservoir and the resulting net power are shown as a function of the mass flow for both the reference case and for changed reservoir conditions. The lower two plots in figure 6 show the corresponding exergy losses.

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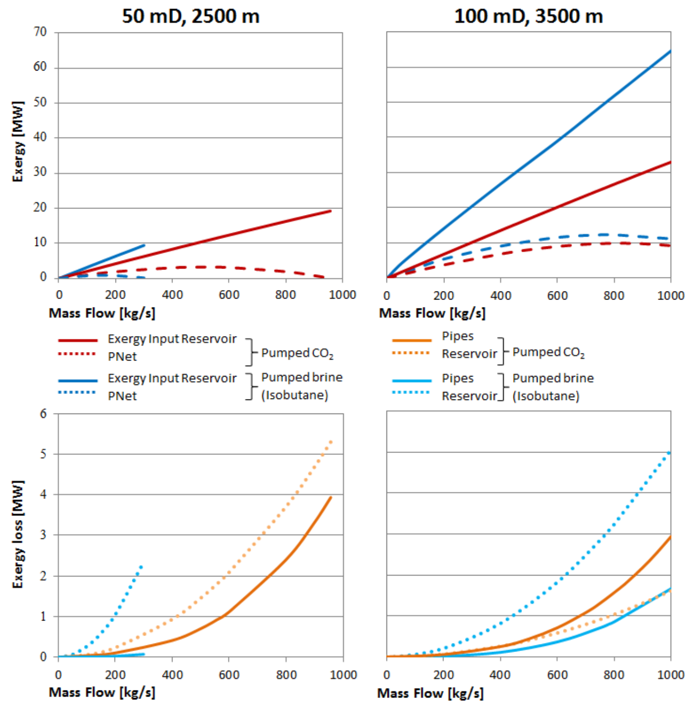

Figure 6: Comparison of exergy transfer and exergy losses for NLGP and brine based systems.

It is obvious that the amount of absorbed heat increases linearly for both studied reservoir cases. As the mass flow increases, the pressure losses in the pipes and in the reservoir also increase. The quadratic rise of the exergy losses deviates depending on the geothermal fluid. In the reference case, the limiting factor for the brine (isobutane) system is the pressure loss in the reservoir. For an increased permeability, i.e. 100 mD and reservoir depth of 3500 m, the pressure loss is reduced so significantly that the net output is even greater than that of the NLGP system. In this case the net output for both systems reaches a maximum at similar mass flow rates. Due to the higher isobaric heat capacity of brine, compared to CO_2, a larger amount of heat is transferred from the reservoir in the indirect hydrothermal system. Although the reservoir conditions are also of energetic advantage for the NLGP system, the high flow velocities of the CO_2 limit the net output. In contrast to the indirect system the pressure loss of the wells is the limiting factor for the NLGP system.

The evaluations indicate that the net power output strongly depends on the conditions of the reservoir and also confirm the results of Adams et al. [2]. In summary CO_2-based systems are advantageous to (indirect) brine-based systems for shallower depths and low permeabilities. The higher the reservoir permeability, the more the viscosity advantages of CO_2 become less important and the greater heat absorption capacity of the brine leads to a higher net output of conventional plants.

Analogous to conventional power plants, the ambient temperature or the site-specific boundary condition for recooling has a significant influence on the performance of the power plant. The NLGP concept and the indirect plants with brine as geothermal fluid and isobutane are investigated regarding their sensitivity to changed ambient temperatures, i.e. the heat sink temperature. Figure 7 shows the analysis results. The middle column for 15 °C corresponds to the reference case.

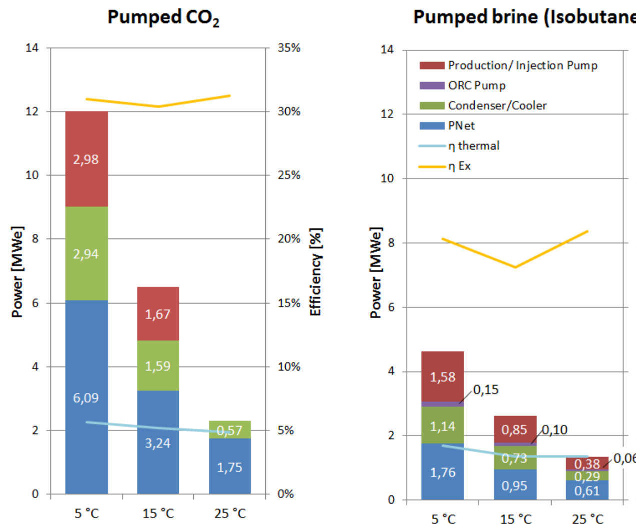

Figure 7: Impact of the ambient air (heat sink) temperature on the electric power output of NLGP and brine-based systems.

If the ambient air temperature is reduced from 25°C to 5°C, the output of the NLGP system is five times higher and the net output three times higher. The lower the ambient air temperatures, the lower is the injection temperature of the CO_2 and the higher is the averaged density of the fluid in the injection well. Under constant reservoir conditions, the difference in the average density between the injection and production well therefore increases, resulting in an enhanced thermosiphon effect at lower ambient air temperatures. Furthermore, the amount of heat absorbed in the reservoir increases with decreased injection temperature, which can also be seen in the larger parasitic load of the cooling system. In addition, with lower ambient air temperature both the condensing temperature and the condensing pressure decrease. This results in a lower turbine back pressure. The enthalpy difference and thus the power output of the turbine are accordingly higher.

At an ambient air temperature of 25°C, the entire process runs in the supercritical state area of CO_2. The additional use of a compressor cannot increase the net output due to the energy-intensive compression in the supercritical state. Powered entirely by the thermosiphon, the system still achieves a higher net output, compared to the brine-based systems, even at ambient temperatures of 25°C, under the given reservoir conditions. In contrast to the brine (isobutane) system, the dependence between density and fluid temperature of the CO_2 results in a higher sensitivity on ambient temperature changes of the NLGP system. However, for low ambient temperatures, e.g.

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5 °C, NLGP systems can achieve an even greater net power output.

TURBINE DESIGN CONSIDERATIONS

Initial blade path calculation and design considerations were carried out with Siemens in-house software tools on the basis of the thermodynamic calculations described above. The pumped NLGP system and the brine (isobutane) system were investigated. For both applications highly efficient SST600 turbine modules were chosen consisting of reaction blades and turning at net frequency. Figure 8 shows the comparison of the CO_2 turbine and isobutane turbine for the base case. For both turbines enhance sealing systems have to be applied. However, due to the flammability of isobutane the leak tightness requirements will be significantly higher for the isobutane turbine. In table 2 the most relevant thermodynamic design conditions are listed for both turbines.

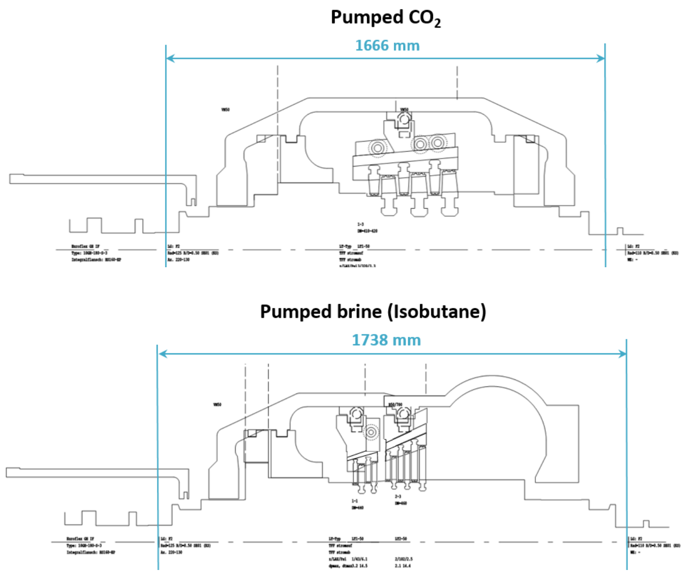

Figure 8: Scaled representation of the CO_2 turbine (top) and the isobutane turbine (bottom) of the reference case.

Table 2: Thermodynamic design conditions for the CO_2 and the ORC turbine are geothermal base case conditions

Value		Unit	CO_2 turbine (~7MW)		Isobutan turbine (~3MW)	
p_{in}	p_{out}	[bar]	118.9	61.3	10.1	3.3
T_{in}	T_{out}	[°C]	60.0	22.9	66.6	34.8
$\dot{m}$		[kg/s]	514		74.4	
$\dot{V}_{in}$	$\dot{V}_{out}$	[m³/s]	1.21	1.99	2.83	9.0
Δh		[kJ/kg]	14.6		39.8	
Δp		[bar]	57.6		6.8	

Because of the almost sixteen times higher density of the CO_2 the volume flow in the turbine inlet is less than half compared to the isobutane turbine even though the CO_2 mass flow is almost seven times larger. The near-critical expansion of CO_2 results in a small density difference compared to isobutane, so that the increase in volume flow during the expansion is also low leading to a small widening of the flow path. Overall, blade path efficiencies for both turbines of approx. 91% can be achieved. Due the significant higher pressure differences the internal leakages of the CO_2 turbine will be higher compared to the ORC turbine resulting in a lower overall efficiency.

The large pressure difference with simultaneous low enthalpy drop in the CO_2 turbine leads to comparable large bending forces in the airfoils. As a result, an enlargement of the blade roots and the hub diameter is necessary to avoid impermissible stresses in the blade roots and airfoils, which is a significant difference compared to CO_2 turbines considered for fossil applications. To make this clear the expansion line of the CO_2 turbine for the NLGP was compared with the expansion lines of CO_2 turbines for waste heat recovery (CCPP) applications presented in [12], which is illustrated in figure 9 and in figure 10.

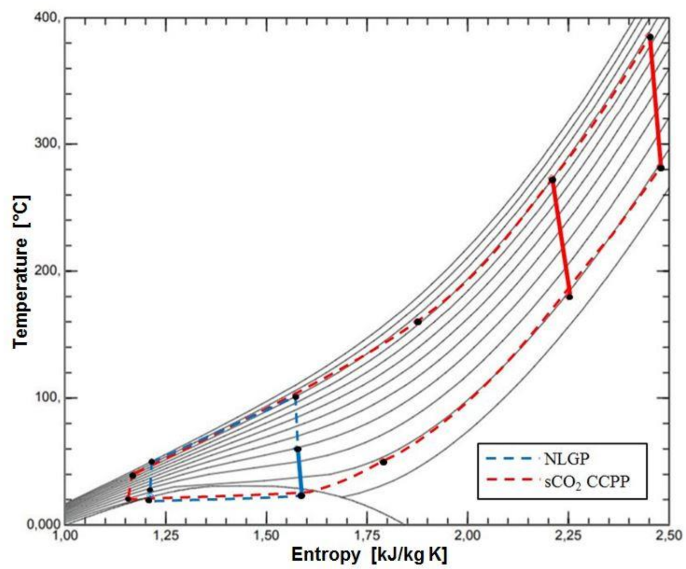

Figure 9: Comparison of the CO_2 expansion (bold lines) for geothermal power cycle and a fossil heat recovery application in a T-s-diagram.

It can be observed that the gradient Δp/Δh is significant larger for the geothermal application which confirms the described design result for the NLGP turbine. Especially for large scaled applications with higher power output this can be a limiting factor so that optimized design concepts need to be developed. A low-speed operation mode for example could increase the number of stages and thus decrease the pressure drop across a single turbine stage.

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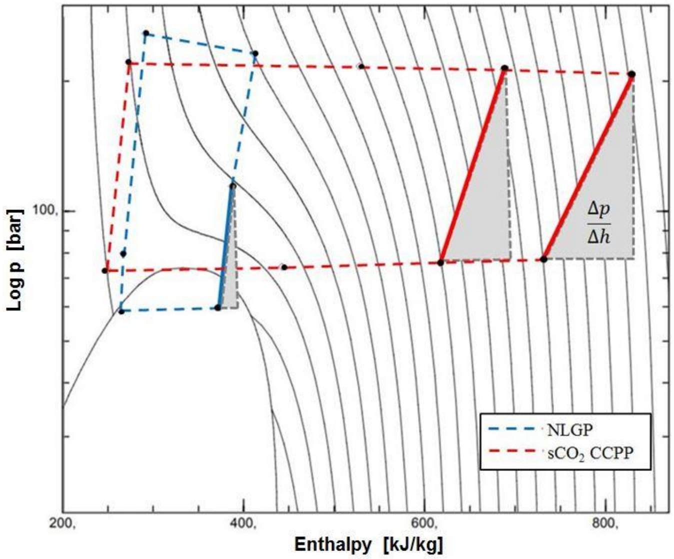

Figure 10: Comparison of the CO_2 expansion (bold lines) for geothermal power cycle (blue) and a fossil heat recovery application (red) in a log p-h-diagram.

The impact of varying reservoir conditions on the turbine design was investigated exemplarily for an increased permeability of 100 mD and a drilling depth of 3500 m. The resulting thermodynamic design conditions are summarized in Table 3.

Table 3: Thermodynamic design conditions for the CO_2 and the ORC turbine at modified geothermal conditions (3500m,100mD)

Value		Unit	CO_2 turbine (~19 MW)		Isobutan turbine (~29 MW)	
p_{in}	p_{out}	[bar]	159.8	61.3	18.0	3.3
T_{in}	T_{out}	[°C]	86.6	22.9	97.4	41.4
$\dot{m}$		[kg/s]	820		531	
$\dot{V}_{in}$	$\dot{V}_{out}$	[m³/s]	1.93	3.62	10.92	66.93
Δh		[kJ/kg]	26.5		61.3	
Δp		[bar]	98.5		14.7	

Due to the changed process parameters, the mass flow in both turbines increases. The thermodynamic analysis shows that the geothermal mass flow of the brine (isobutane) system and thus the amount of heat absorbed in the reservoir is considerably larger under changed reservoir conditions. This leads to a seven times larger mass flow of isobutane to absorb the amount of geothermal energy. While the inlet volume flow of the isobutane turbine increases almost by a factor of 4, it is not even doubled in the CO_2 turbine. This will result in a significantly larger isobutane turbine for changed reservoir conditions due to the strong increase in volume flow in the isobutane cycle.

Geothermal power plants are characterised by high heat dissipation in the condenser and a low average thermodynamic temperature. Thus, the required heat exchanger surfaces are large and considerably increase the costs of the cooling system. Basic design calculations considering a shell-and-tube heat exchanger were carried out resulting in heat exchanger surfaces for the NLGP- and the (indirect) brine-based (isobutane in the secondary loop) system. Figure 11 illustrates the ratio of the respective heat exchanger surfaces depending on the different reservoir conditions.

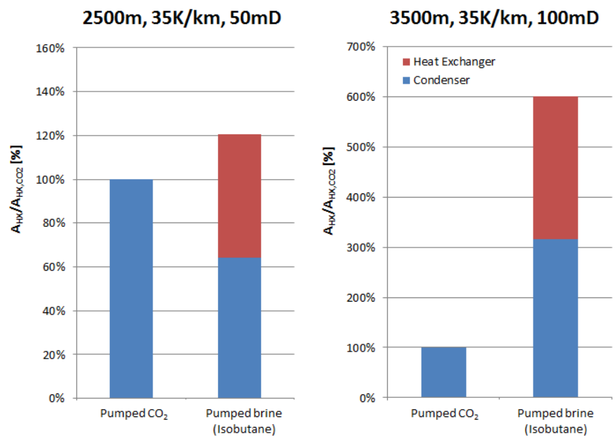

Figure 11: Comparison of heat exchanger surfaces for NLGP and brine based systems for different reservoir conditions (depth, geothermal gradient, permeability).

At base case conditions, the overall heat exchanger surface of the ORC system is approximately 20 % larger than that of the CO_2 plant. Although only half of the amount of thermal energy is transferred in the isobutane-condenser, it already represents more than 60% of the CO_2 condenser, which can be explained by the reduced heat transfer in the ORC condenser. In contrast to the NLGP system, the isobutane is superheated at the condenser inlet. In this gaseous state, the heat transfer is very low, leading to a large total heat exchange surface. Combined with the additional heat exchanger for the secondary cycle, the total required exchange surface of the brine (isobutane) system is larger.

For the modified reservoir conditions, i.e. 3500 m and 100 mD, the transferred exergy in the reservoir is approximately doubled for the (indirect) brine (isobutane) case, which can be seen in figure 5. Thus, the emitted heat in the condenser is even greater than that of the CO_2 plant. As a result, the overall required heat exchange surface is approximately six times larger.

Based on the initial design assumptions mentioned above, NLGP's surface power plant is less complex, has fewer and smaller components than the (indirect) ORC system. However, this economic advantage is partly compensated by the higher pressure level of the CO2 cycle, which leads to greater wall

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thicknesses of the components. To evaluate the different designs for the overall power plant, a detailed comparative design study would be the next step However, a first generic economic assessment for NLGP based on LCOE calculations have been carried out, which is described next.

ECONOMIC EVALUATION

According to Bielicki et al. [6] the levelized costs of electricity (LCOE) for NLGP systems are decreasing when the power plant capacity is increasing from N=1 to higher coordination numbers until a minimum appears to be reached at N=5. Therefore, two N=5 cases were investigated for the economic evaluation.

In Table 4 the geologic properties of the reservoirs, the thermal boundary conditions of the power plants and the most relevant thermodynamic assumptions and characteristics for the two considered cases are given. They were chosen to represent typical conditions of reservoirs, which are common, where NLGP is feasible and geothermal systems are not economical. During the assumed operation lifetime of 25 years, no thermal depletion of the reservoirs was assumed.

Table 4: Boundary conditions of the two considered cases for the economic evaluation**.**

	Case 51 MW_e	Case 157 MW_e
Coordination number N [-]	5	5
Depth [m]	2500	3500
Permeability [mD]	50	100
Temperature gradient [°C/km]	35	35
Well diameter [m]	0.41	0.41
Cooling type	Wet cooling tower	Wet cooling tower
Ambient air heat sink temperature [°C]	15	15
Approach temperature [°C]	15	15
P gross [MW_e]	79	255
P net [MW_e]	51	157

The cost assessment is performed for a project with brownfield approach. This means, that an already developed well field with existing wells, which can be re-used as CO_2-injection wells, is assumed. This may be the case, for example, for carbon capture and storage (CCS) systems and for depleted gas or oil fields especially when CO_2 is injected for enhanced oil recovery (EOR) or enhanced gas recovery (EGR).

The NLGP energy system may be structured in two parts: the well field including surface piping, and the surface power plant. Beside well drilling as main cost driver, the wellfield costs include all efforts for wellfield completion e.g. costs for monitoring equipment. These costs can vary significantly due to project specific boundary conditions such as e.g. soil properties, available infrastructure and monitoring or regulative requirements. For the first cost assessment, estimates by Flaming et al. are used [7]. They are based mainly on the detailed cost analysis for geologic CO_2 sequestration published by the United States Environmental Protection Agency, EPA (2008) [8], and well drilling estimates from the Geothermal Electricity Technology Evaluation Model (GETEM) [9].

Cost estimates for the CO_2 pipelines are also subject to a certain dispersion reflecting variations caused by the impact of specific terrain, land use, and population density. In the present investigation the costs for the 65 km surface piping are calculated on average with ca. 2.2 $/(km m), including all necessary equipment, corrosion protection cost as well as all efforts e.g. for planning engineering and installation. Considering published data [8, 10] this approach is assumed to be conservative.

The estimated costs of the power island include all necessary systems, infrastructure, buildings, efforts for planning, engineering, commissioning etc. that are typically within the scope of a turnkey project. An additional 10% in costs is assumed for project development by the project owner. The power plant costs were derived by adjusting components for conventional power plants. Preliminary calculations, based on Siemens' product portfolio and in-house data show that the main cost drivers are related to the heat rejection, i.e. cooling tower, and gas cooler. Favourable cooling conditions, for example access to direct cooling at coastal or offshore locations, can therefore lead to significant cost reductions. In sum, the current cost estimates for the surface plant, including piping, are 300 M$ (52 MW_e) and 480 M$ (157 MW_e). Further cost optimization potentials, e.g. by improving the heat rejection systems, seem likely and need to be investigated.

To evaluate the economic competitiveness of a NLGP power plant, the LCOE can be compared. The LCOE are calculated based on assumptions and boundary conditions following Lazard's latest comparative LCOE analysis [11].

Table 5: Assumptions for LCOE calculation for the two example NLGP systems.

Capacity factor	90%
Operation lifetime	25 years
Project development/ construction time	1 year
Annual O&M cost	360 – 630 $/kW
O&M cost escalation rate	2.25%
Equity rate	40%
Cost of equity	12%
Cost of debt before tax	8%
Debt payback period	Operation lifetime
Principal payment type	Levelized debt service
Combined tax rate	40%
Depreciation schedule	Modified accelerated cost recovery system (MACRS) 5-years

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The capacity factor defines the assumed operational time of the power plant.

Operation and maintenance (O&M) cost for the wellfield and the surface power plant are for first calculations estimated in accordance with the assumptions used in GETEM [9] as a percentage of the capital costs. The resulting annual costs seem quite high, compared to experience with conventional power plants. Evaporated cooling water is considered with 1 $/m³.

In sum, the O&M costs contribute up to 40% to the estimated LCOE. Therefore, more detailed cost investigations should be conducted in a next step to evaluate the differences between NLGP systems and geothermal power plants regarding O&M efforts.

Table 6 shows the resulting LCOE compared to Lazard's [11] results for some conventional and renewable technologies in 2018. No revenues or costs of CO_2 storage are included in this comparison. These will have to be considered in addition.

Given the presented boundary conditions and assumptions, Table 6 shows that a 52 MW_e NLGP power plant may be too small to reach competitiveness. In contrast, the calculated LCOE for the 157 MW_e example NLGP power plant is within the LCOE range that is typical for other baseload-capable power plants, such as coal, nuclear or solar-thermal towers, the latter with energy storage. It must be emphasized that the economic assessment strongly depends on the geologic properties of the reservoir. As the presented evaluation is not based on reservoirs which were selected especially for conditions optimal for NLGP, significant lower LCOE can be expected with the right reservoirs. These need to be identified in a next step. This aspect is confirmed in principle by Levy et al. [13] who have determined the LCOE of approximately 16 $ ct /kWh for a 30 MW application (green field approach) for a Mexican reservoir with special geologic conditions.

Table 6: LCOE Comparison for various baseload-capable power plants

	Technology	LCOE [$ ct/kWh]
Lazard (2018) [11]	Solar Thermal Tower with Energy Storage (110 -135 MW)	9 – 18
	Geothermal (20 -50 MW)	7 – 11
	Nuclear (2200 MW)	11 – 19
	Gas Combined Cycle (550 MW)	4 – 7
	Coal (600 MW)	6 – 14
NLGP (brownfield)	Case 52 MW	20
	Case 157 MW	12

SUMMARY & OUTLOOK

The thermodynamic evaluation show that CO_2-based geothermal power plants can produce significantly more output than conventional (indirect) hydrothermal systems, particularly at "shallow" depths of 2-3 km and low reservoir permeabilities. Higher reservoir temperatures, e.g. due to greater reservoir depth, reduce the kinematic viscosity of the brine and thus the pressure losses occurring in the reservoir. The greater the reservoir permeability and the higher the reservoir temperature, the greater the energetic advantage of indirect brine systems with a secondary ORC (isobutane) process.

While the variable density of the CO_2 leads to a higher performance for relatively shallow reservoir depths, due to the thermosiphon effect, this property also results in a greater sensitivity of NLGP systems to cooling conditions, compared to brine-based geothermal systems, where low ambient air heat rejection temperatures are particularly advantageous for NLGP systems.

Initial design considerations showed a compact turbomachinery layout leading to a more compact design compared to brine/ORC systems especially for larger power output. Due to the expansion close to the critical point some different design requirements compared to fossil application needs to be considered. Thus, optimized designs are necessary which needs to be elaborated in the next future.

The calculated LCOEs for the example cases show, that with suitable geologic properties, NLGP systems can generate electricity at competitive costs, when a brownfield approach is used. Reservoirs with more beneficial geologic boundary conditions will lead to a further significant reduction of LCOEs. Thus, suitable locations need to be identified; enhanced cost analyses should be carried out, to determine the boundary conditions for competitive NLGP systems even with greenfield approach.

Including the costs of CO_2-emissions and the economic benefits of providing CO_2 storage in the cost comparison can lead to a further shift in favour of NLGP systems.

NOMENCLATURE

CC	Carbon Capture
CCS	Carbon capture and storage
CCPP	Combined cycle power plant
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
GETEM	Geothermal Electricity Technology Evaluation Model
Geo	geologic
h	Enthalpy [kJ/kg]
LCOE	Levelized costs of electricity
$\dot{m}$	Mass flow [kg/s]
mD	millidarcy
N	Coordination number
NLGP	Next Level geothermal Power Plant
ORC	Organic Rankine cycle
O&M	Operation and maintenance

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p Pressure [bar]
P Power output [MW]
ref Reference
REFPROP REFerence fluid PROPerties
Res *geologic reservoir*
sCO_2 Supercritical Carbon Dioxide
T Temperature [°C or K]
T_m Mean Temperature [°C or K]
TTD Terminal Temperature Difference [K]
$\dot{V}$ Volume flow [m^3/s]
w/s Water/Steam
x Steam quality [-]
Δ Difference
η Efficiency [%]
κ Permeability
μ Dynamic viscosity
ζ Pressure loss coefficient
ρ Density [kg/m^3]

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