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Zero Emission Geothermal Flash Power Plant

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Abstract

The successful exploitation of geothermal energy for power production relies on the availability of nearly zero emission and efficient technologies. Two zero emission flash plant layouts, with full reinjection of the geothermal fluid (non-condensable gas included), are considered. This paper focusses on the CO_2 issue, and therefore only the carbon dioxide is considered as non-condensable gas present in the geothermal fluid; the CO2 flow is separated, compressed, and reinjected with the geothermal fluid. Both the reservoir and the power plant are simulated. A first scheme of plant presents a conventional layout in which the CO_2 is separated and compressed after the condenser. The second scheme presents a plant layout that allows the separation of the CO_2 at higher pressure with respect to the conventional layout, thus reducing the requested power consumption.
The conventional plant scheme performs always better at higher temperature and at lower concentration of CO_2. The new layout results better for low temperature and higher gas content.

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Keywords: Geothermal plant; geothermal energy; ;CO_2 separation; CO_2 reinjection; zero emission; non-condensable gas; reservoir simulation.

1. Introduction

The successful exploitation of geothermal energy for power production relies on the availability of nearly zero emission and efficient technologies, able to provide flexible operation. The binary cycle and flash steam technology are both eligible technologies for geothermal power generation. Non-condensable gases, possibly present in the

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geothermal fluid, represent an important issue as far as environmental aspects are concerned. Due to the climate change concern, major attention is presently paid to the CO_2 content.

In the traditional flash plant layout non-condensable gases are extracted from the condenser, and, though the most harmful gases are usually treated and disposed, the CO_2 still represents an issue, because it is commonly released in the ambient. Flash technology is a well established technology, generally adopted when the geothermal fluid consists of a mixture of liquid and vapors at wellhead, with temperature higher than about 160-180 °C. The main feature of this technology is the adoption of a direct cycle, whereby the geothermal fluid coming from wellhead is flashed, and separated steam enters a steam turbine, followed by a condenser. The whole plant scheme is then tailored on the geothermal fluid characteristics: salts and non-condensable gases are often present in the geothermal fluid. The geothermal fluid is treated before entering the turbine [1] and, if non-condensable gases (NCG) are present, an extraction system is required, in order to allow condenser proper operation; afterwards, depending on the chemical composition, separated NCG are treated in a removal plant or directly released in the ambient. The chemical composition of the geothermal fluid is strongly site dependent: as far as the gaseous phase is concerned, CO_2 is often present, and H_2S may be present as well; sometimes hydrocarbons are also present. As reported in [2], steam from Italian steam dominated geothermal fields may be available with a temperature of about 200°C, with a non-condensable gas content ranging from 4 to 10% by weight. In [3] the non-condensable gas are mixed with inlet air in the gas turbine and burnt in the combustion chamber. Up to a few years ago, the adoption of a direct contact condenser, coupled to a wet cooling tower, was an easy and common technical solution; the flowing of the condensed geofluid through the cooling tower, however, prevents a thorough separation of the geothermal fluid loop from the ambient. In recent years, surface condenser are becoming popular, as they allow more effective removal and treatment of the NCG [4]. The concern for “climate change” encourages the investigation of possible power plant schemes which do not release CO_2 in the atmosphere.

The binary cycle technology is accomplished by means of two completely separated cycles, a geothermal loop, and a power cycle (ORC or Kalina cycle) [5]. It is commonly adopted for all liquid sources or medium-low-temperature sources (generally between 100-170 °C). It entails an important advantage, i.e. the thorough confinement of the geothermal fluid in a closed loop, which is beneficial to the environment (possible pollutants are not released into the ambient but reinjected underground). A common configuration of binary cycle technology is equipped with submersible pump that can guarantee a stable well production, but that is subjected to scaling, cavitation that determine a short lifespan.

This paper focusses on flash technology, and, in order to realize a zero-emission plant, with full geothermal fluid reinjection, the separated CO_2 is compressed, liquefied and mixed with the geothermal condensate prior to reinjection. Two different layouts of flash plant without gas emissions are considered for the temperature range of 150°C-200°C:

- a standard flash configuration: the separated CO_2 , removed from the condenser, is compressed, liquefied and mixed with the geothermal condensate prior to reinjection. The compression ratio required is high and the consumption of the compressor significantly affects the net power production.
- an alternative flash plant layout: CO_2 separation occurs at wellhead, so that the compression ratio required is lower than in previous case.

The thermodynamic model adopted to study the performances of the plants is validated with experimental results available in literature. This paper focusses on the CO_2 issue, and therefore only the carbon dioxide is considered as non-condensable gas present in the geothermal fluid. The work proposes the comparison of these layouts on an innovative and coherent basis, starting the comparison from the geothermal reservoir conditions, according to the approach presented in [6] and aiming at an integrated- reservoir-plant approach [7].

The trade-off point between the two flash plant layouts, and, afterwards, between the best of them and the binary plant, depends on both technical and economic aspects. In this paper, however, the focus will be on technical aspects typical of the flash configuration, considering plant performance; environmental aspects and other possible peculiar technical problems (e.g. scaling) and economic aspects are left for future work.

Nomenclature

C_D	drawdown coefficient, bar/(kg·s)	P_{fl-trb}	inlet turbine pressure, bar
$\dot{m}_{Wh}$	well mass flow, kg/s	$\dot{m}_{ORC}$	ORC cycle mass flow, kg/s
p_{Wh}	Wellhead pressure, bar	$\dot{W}_{CP1}$	compressor power, kWe
$\dot{W}_{HRJ}$	Rejected heat, kWe	$\dot{W}_{CP2}$	intercooled compressor power, kWe
$\dot{W}_{TRB}$	turbine power, kWe	$\dot{W}_{PMP}$	pumps power, kWe

2. Simulation model

The simulation model is realized by means of a commercial process simulator Aspen Plus®. This process simulator is commonly used for power plants performance simulation; the extension down to the geothermal reservoir conditions represents the innovative aspect of this work; only an all-liquid reservoir is considered in this study, and, moreover, it is assumed that operating conditions are such that the flow remains in liquid phase at least until the inlet of the well. Because the chemical composition of geothermal fluid flow is strongly site dependent, the plant scheme needs to take into account the fluid peculiarities. In the present work attention is paid to the possible presence of CO_2 dissolved in the liquid geothermal fluid in the reservoir: the chemical reactions related to the carbonic acid formation and its equilibrium is considered with the Electrolyte Non Random Two Liquid thermodynamic model. The investigation on the effect of dissolved salts on plant performance is left to future work.

2.1. Geothermal fluid loop

The geothermal fluid flow originates ideally from an undisturbed point of the reservoir, and passes then through the production well, is exploited in the plant, and goes finally to the reinjection well, in order to go back to the reservoir.

The well-reservoir flow is simulated considering a horizontal mass flow in a porous medium, followed by a vertical flow in a pipe, under steady conditions. In the reservoir the flow obeys to the Darcy law, and therefore the pressure difference between an undisturbed point in the reservoir and the well feed is proportional to the geothermal fluid mass flow: this is easily accounted for by assuming a drawdown coefficient, C_D [4], defined as

$$C_D = \frac{\Delta p}{\dot{m}} \tag{1}$$

where Δp is the pressure difference between the undisturbed reservoir conditions and the well bottom, under flowing conditions.

The flow in the well has been diffusely investigated, and several simulation models exist [8]. The geothermal fluid flow is, as already stated, single phase (liquid) at the well bottom, but, if no submersible pump is adopted, it is likely to flash to double phase flow when flowing into the well: the main issue of the simulation process is therefore the void fraction calculation and the pressure drop evaluation. The process simulator adopted in this work allows choosing among several correlations of general purpose for the evaluation of the void fraction in the well. Preliminary calculations were conducted in order to select the best performing correlation based on the data provided in [9]. The correlations by Beggs-Brill, Orkiszewski and HTFS (Heat Transfer and Fluid Flow Service) were tested: though often adopted in the frame of geothermal calculations, the Orkiszewski correlation gave the worst result; the correlations of Beggs-Brill and HFTS provided better results, similar to each other. Even if the HTFS correlation yielded a slightly better result, the Beggs-Brill correlation was finally selected, thanks to the fact that it is quite largely adopted in geothermal applications, and because HTFS was actually derived for small pipe diameters.

Due to the lack right now of available information for the complete set of well-reservoir parameters for a specific geothermal site, common values (Table 1) are selected; calculations with reference to a specific geothermal site is then left to future work.

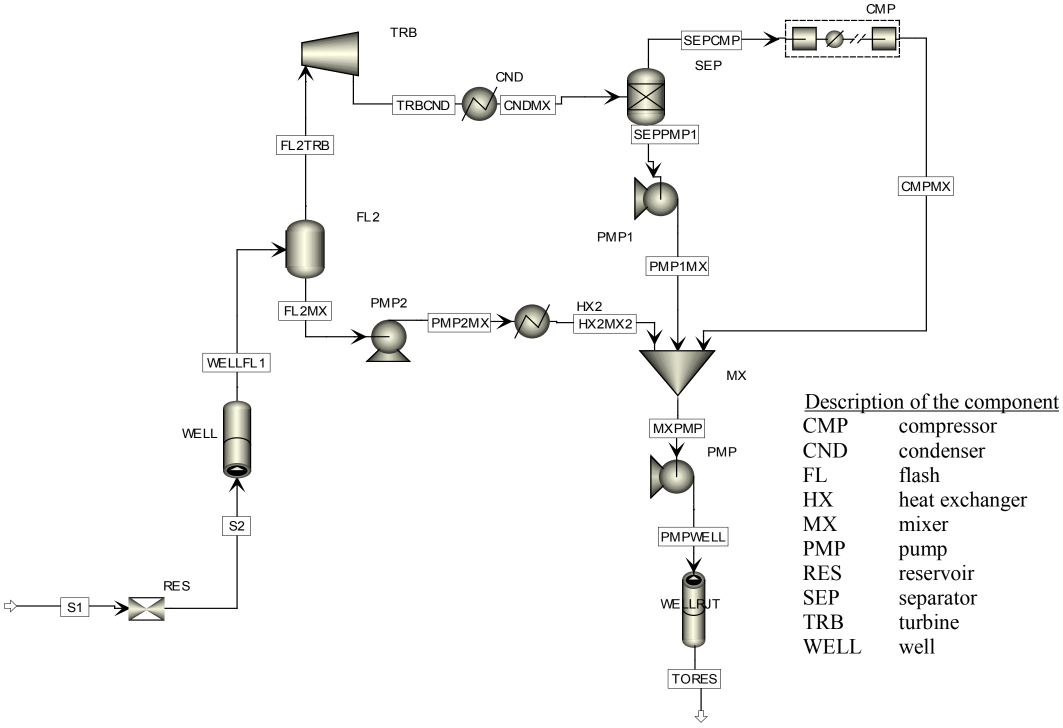
Table 1 Well and reservoir assumptions

Parameter		
Drawdown coefficient	C_D	0.4 bar/kg·s
Reservoir pressure	p_{res}	100 bar
Well depth	L	1000 m
Well diameter	D	0,339 *m*

The same model used for the reservoir and production well flow is the used for the reinjection process. In this case, however, the flow is single phase, liquid, but the CO_2 presence requires high pressure and possibly the adoption of a reinjection pump in order to have the pressure of the reservoir.

2.2. Conventional flash layout with CO_2 separated at the condenser

In existing flash plants the geothermal fluid coming from wellhead is flashed, and separated steam enters a steam turbine, followed by a condenser. In this case, the CO_2 fraction possibly present is sent to the turbine, and expands together with the steam, providing further work; however, an extraction system (a steam ejector or gas compressor) is required in order to remove the CO_2 from condenser and allow condenser proper operation. This situation may be convenient because in old, traditional plants CO_2 is compressed up to the atmospheric pressure, and then released into the ambient. In the present work, no gaseous flow release is assumed, and the separated CO_2 must be reinjected together with the liquid geothermal fluid. In order to accomplish this process, the CO_2 need to be compressed up to a pressure suitable for the mixing with the geothermal fluid prior to the reinjection process. The scheme of plant is proposed in Figure 1.



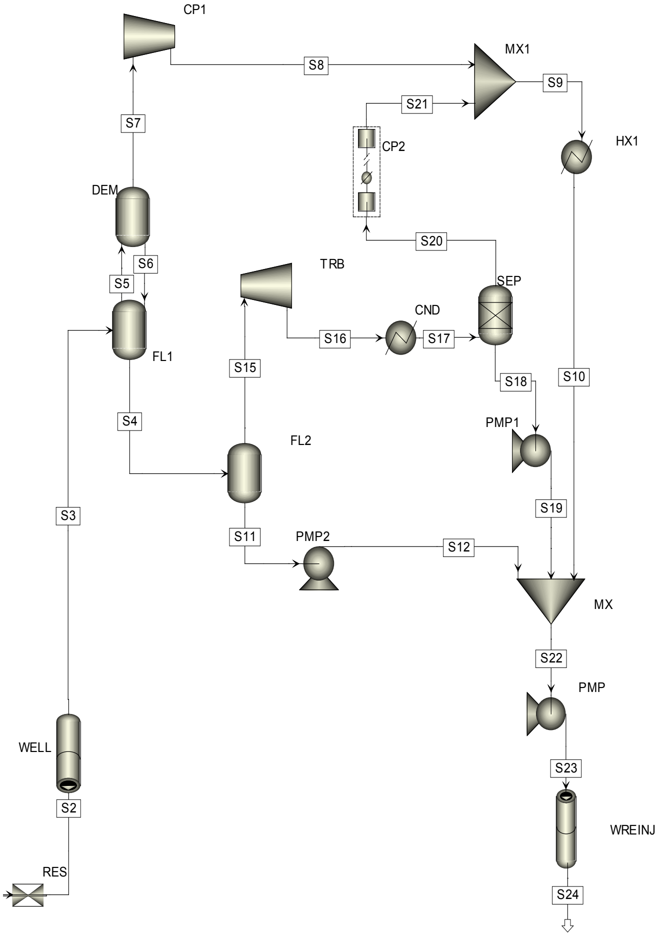
Description of the component

CMP	compressor
CND	condenser
FL	flash
HX	heat exchanger
MX	mixer
PMP	pump
RES	reservoir
SEP	separator
TRB	turbine
WELL	well

Figure 1 Total reinjection flash plant with CO_2 separated at the condenser

2.3. Alternative flash plant layout with CO_2 separated at the wellhead

Aiming at full reinjection, and in order to reduce the compressor power consumption, the CO_2 fraction can be separated at the wellhead, according to the plant scheme presented in Figure 2: with respect to the conventional scheme extra components are added due to the requirement of CO_2 reinjection.



Description of the component

CMP	compressor
CND	condenser
DEM	demister
FL	flash
HX	heat exchanger
MX	mixer
PMP	pump
RES	reservoir
SEP	separator
TRB	turbine
WELL	well

Figure 2 Total reinjection flash plant with CO_2 separated at the wellhead

The geothermal fluid coming from wellhead, which is a two phase mixture, undergoes a small pressure decrease (about 1%) which is enough to let most of the CO_2 pass in the gaseous phase of the flow. After that, the mixture is cooled in a sort of demister, whose temperature is controlled by means of water coming from a cooling tower, the steam is condensed, in such a way that the gaseous flow contains mainly CO_2, which is directly sent to the CO_2 compressor. In this way no work is obtained by CO_2 during turbine expansion, but a much lower power is required for the CO_2 compression. The high pressure CO_2 flow is afterwards cooled down to a temperature lower than the critical temperature, so that it becomes liquid, and can be mixed with the liquid fraction from the second flash and the condensate; the reconstituted geothermal fluid is finally sent to the reinjection well.

On the water flow side, the scheme is similar to the conventional case: the flow is flashed, and the steam fraction is sent to the turbine; however, the small quantity of CO_2 still present in the flow requires the adoption of an extraction system at the condenser and of a further compressor.

For both plant layouts, the performance simulation requires the evaluation of the well productivity curve and, based on that, the optimization of the pressure of the flash chamber before the steam turbine, which is the most important operating parameter of a flash plant [2] in order to provide the highest possible electric power.

2.4. Evaluation of geothermal fluid properties

The liquid flow from the well is considered as pure water with a certain molar fraction of dissolved CO_2. In order to properly describe the behavior of the mixture, the chemical equilibria that bring to the formation of carbonic acid must be considered, which implies that the thermodynamic model must be able to consider an electrolyte system. The Electrolyte Non-Random-Two-Liquid thermodynamic model, suitable for these systems, was selected and validated against experimental data available in open literature. Several authors were considered [10]–[12].

In Figure 3, the comparison with data reported in [11], shows that the selected thermodynamic model is appropriate for describing the system. The thermodynamic model is used in frame of the software Aspen Plus V.9, with built-in parameters, for the assessment of the performance of the simulated power plants.

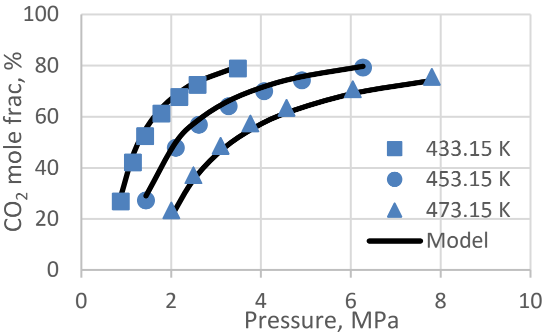


Figure 3 Vapor phase composition, comparison of the thermodynamic model against experimental data [11], the complement to 100 is the mole fraction of the water in vapour phase.

3. Performance evaluation and discussion

Plant performance is evaluated with reference to the assumptions detailed in Table 2:

Table 2 Basic assumptions

Parameter	
Ambient temperature	15 °C
Condenser cooling medium	Water
Turbine isentropic efficiency	0.9
Pump hydraulic efficiency	0.8
Organic-electric efficiency	0.95
CO_2 mixing pressure	80 bar
Condensing temperature	32°C
Heat rejection electric consumption	0.01 $MW_e \cdot MW_{th}^{-1}$

Performance evaluation is conducted for several values of reservoir temperature (150°C, 175°C and 200°C) and two values of CO_2 content (1% and 5%). A parametric analysis is performed in order to describe the behavior of the two layouts: the mass flow rate from the well is varied (and the corresponding pressure at the wellhead is determined) as well the pressure at the flash chamber before the turbine (in order to depict the trend of the power produced).

The best results for each investigated condition are reported in Table 3 for the flash plant with CO_2 separated at the condenser and in Table 4 for the flash plant with CO_2 separated at the wellhead.

With the first plant layout, the net power increases with the temperature of the reservoir, but decreases with concentration of the CO_2, this mainly because of the higher influence of the compressor consumption for the carbon dioxide. For the case with 5% of CO_2 at 150°C it not possible to produce electric power. With low concentration of carbon dioxide the effect of the gas compression and reinjection is limited. For the higher concentration, the power of the CO_2 compressor alone can halve the power of the turbine.

Table 3 flash plant with CO_2 separated at the condenser

		150 °C		**175°C**		**200°C**	
		1%	**5%**	**1%**	**5%**	**1%**	**5%**
$\mathbf{P_{wh}}$	bar	1.98	0.00	2.59	5.14	5.39	5.60
$\mathbf{P_{fl\text{-}trb}}$	Bar	0.50	0.00	1.00	1.25	1.50	1.75
$\dot{m}_{wh}$	kg/s	65	0	90	135	110	145
$\dot{W}_{TRB}$	kWe	2303.53	0	4713.01	7729.86	7892.53	11546.50
$\dot{W}_{CP1}$	kWe	437.28	0.00	607.55	4555.42	744.40	4908.11
$\dot{W}_{PMP}$	kWe	871.48	0.00	1211.49	1782.72	1483.72	1918.49
$\dot{W}_{HRJ}$	kWe	77.97	0.00	192.73	12.11	342.65	42.61
NET POWER	kWe	**916.81**	**0.00**	**2701.25**	**1379.61**	**5321.76**	**4677.29**

With the second plant layout, also the temperature of the "demister" is varied. The amount of the water condensed is reported. The heat rejected from this component has only limited effect on net power production.

Table 4 flash plant with CO_2 separated at the wellhead

		150 °C		**175°C**		**200°C**	
		1%	**5%**	**1%**	**5%**	**1%**	**5%**
$\mathbf{P_{wh}}$	Bar	3.60	12.36	5.92	13.69	8.65	15.85
$\mathbf{P_{fl\text{-}trb}}$	Bar	0.50	0.50	0.75	1.00	0.75	1.00
$\dot{m}_{wh}$	kg/s	45	65	60	90	85	105
$\mathbf{CO_{2,wh}}$	kg/s	0.45	3.25	0.60	4.60	0.85	5.25
$\mathbf{CO_{2,\,CP1}}$	kg/s	0.42	2.71	0.57	4.27	0.82	5.05
$\mathbf{CO_{2,S5}/\,CO_{2,S7}}$	%	31/97	86/99	25/96	74/99	18/96	58/100
$\mathbf{T_{demister}}$	°C	70	70	80	80	90	90
$\dot{Q}_{DEM}$	kW_{th}	2632.81	1308.74	5017.34	4362.18	11477.17	9960.82
$\mathbf{DEM^{water\ cnd}}$	kg/s	1.04	0.42	1.99	1.49	4.63	3.88
$\dot{W}_{TRB}$	kW_e	1206.30	1810.50	2258.30	3699.92	3915.48	5443.65
$\dot{W}_{CP1}$	kW_e	158.99	478.42	174.50	724.86	202.32	818.90
$\dot{W}_{CP2}$	kW_e	18.96	364.40	18.61	225.19	17.46	131.77
$\dot{W}_{PMP}$	kW_e	478.95	663.60	640.64	944.29	906.99	1076.54
$\dot{W}_{HRJ}$	kW_e	29.52	24.64	59.99	91.44	126.32	152.71
NET POWER	kW_e	**519.89**	**279.44**	**1364.56**	**1714.14**	**2662.40**	**3263.74**

As shown in Table 4 the net power increases with the temperature of the reservoir and also with the concentration of the CO_2. It is notable that for the higher concentration of CO_2 this layout performs better than the other one under 200°C. With this layout for the condition with 5% of CO_2 at 150°C some power is produced.

For both the layout it can be noted that the pressure at the wellhead increases with the increasing of the temperature of the reservoir and the concentration of CO_2. This allows larger mass flow rate to the plant, thus more power. It can be also noted that the power consumption of the reinjection pump (W_{PMP} in Table 3and Table 4) requires a great part of the available energy. A possible way to overcome this drawback is to consider the possibility to reinject the CO_2 thru another well that reaches the bottom of the reservoir: the reinjection pump would elaborate only the mass flow of CO_2. In this work, this option is not considered since it appears more difficult to manage and control the gas solubility with respect to the proposed option of mixing the liquid CO_2 and water at the same pressure (80 bar) before the common reinjection well.

Comparing the values in the Table 3 and Table 4 is evident that the new layout is able to decrease the power consumption in the compression stages, but the power produced from the turbine is much lower. This due to the lower mass flow rate elaborated by the turbine: at same condition both less H_2O and CO_2 pass in vapor phase.

4. Conclusions and future work

The calculations performed show that, at least for the general well-reservoir assumptions herein considered (productivity index, well depth and diameter) the performance of investigated layout are highly affected by the concentration of the carbon dioxide present in the reservoir. In general:

- At higher temperature the conventional layout, even reinjecting the gas, perform better.
- The new layout gives better results at lower temperature, but with higher concentration of CO_2.
- With low concentration of CO_2 the conventional layout performs always better.

The Figure 4summarizes the results obtained.

Future activities will focus on identify a trade-off considering also the economic aspect and an ORC plant.

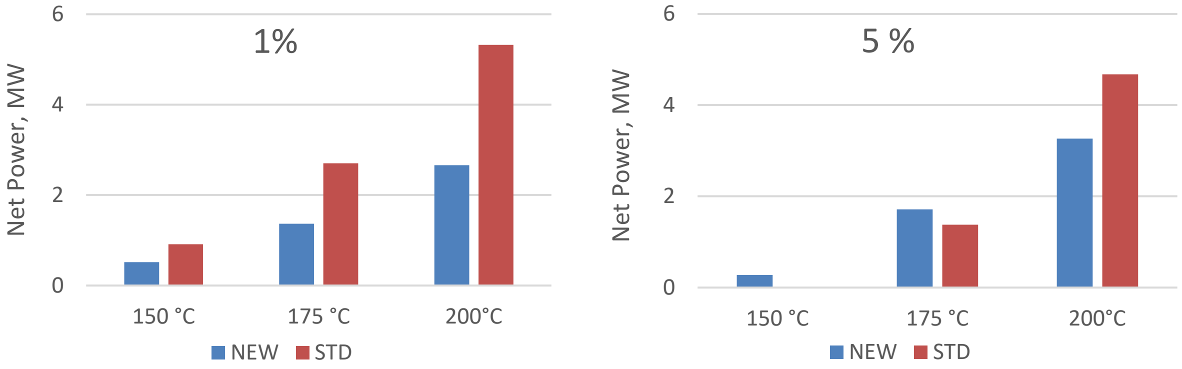


Figure 4 Net power obtained with the reservoir at different temperatures, on the left with CO_2 concentration of 1%, while on the right with 5%

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