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Potential performance of environmental friendly application of ORC and Flash technology in geothermal power plants

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Abstract

The successful exploitation of geothermal energy for power production relies on to the availability of nearly zero emission and efficient technologies, able to provide flexible operation. It can be realized with the binary cycle technology. It consists of a closed power cycle coupled to a closed geothermal loop, whereby the closed power cycle is generally accomplished by means of an organic Rankine cycle (in a few cases the Kalina cycle has been adopted). The confinement of the geothermal fluid in a closed loop is an important advantage from the environmental point of view: possible pollutants contained in the geothermal fluid are not released into the ambient and are directly reinjected underground.
Although a well-established technology in the frame of geothermal applications, the adoption of the binary cycle technology is at the moment typically confined to the exploitation of medium-low temperature liquid geothermal reservoirs, generally between 100-170 °C. The important advantages of the binary cycle technology from the environmental point of view suggest nevertheless that it is worthwhile to investigate whether the application range could be extended to higher temperature reservoirs, and up to which extent. Moreover, the paper investigates the effect of an increasing CO_2 content in the geothermal fluid. The paper compares in a convenient high temperature range of the geothermal source the performance of a properly optimized geothermal ORC plant, with the performance of a modified flash plant, whereby the geothermal steam enters a turbine, and the CO_2 stream is separated, compressed and finally reinjected. An environmentally friendly working fluid, recently introduced in the market, is considered in the ORC optimization process. The performance comparison will involve the assessment of plant net power. As far as the calculations are concerned, the geothermal fluid is assumed to be a mixture of water and possibly CO_2. The auxiliary power consumption is properly accounted for: beyond cooling auxiliaries, a submersible well pump for the ORC plant and a gas compressor for the reinjection of the non-condensable gases in the flash plant are considered.

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1. Introduction

The successful exploitation of geothermal energy for power production relies on to the availability of nearly zero emission and efficient technologies, able to provide flexible operation. In this context, the binary cycle technology could have a chance to enlarge its application range against the conventional flash technology, commonly adopted for the exploitation of medium-high temperature geothermal sources.

Flash technology is a well established technology, generally adopted when the geothermal fluid consists of a mixture of liquid and vapour 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 noncondensable 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. 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 [2]. 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). 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) and may moreover reduce problems related to scaling, which could otherwise be severe. This advantage may lead to an extension of the suggested application for binary plants towards higher temperatures, with the condition that the binary plant is adapted to the considered geothermal source and properly optimized, so that the conversion efficiency is conveniently high.

Paper which compare geothermal flash and binary plants are hardly found in the open literature: in this paper a first attempt is made to compare these technologies on an innovative and coherent basis, starting the comparison from the geothermal reservoir conditions, according to the approach presented in [3] and aiming at an integrated- reservoir-plant approach [4].

The trade-off point between flash and binary technology depends on both technical and economic aspects; in this paper, however, the focus will be on technical aspects, 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_{ORC}	ORC cycle max pressure, bar
$\dot{m}_W$	well mass flow, kg/s	$\dot{m}_{ORC}$	ORC cycle mass flow, kg/s
p_{Wh}	Wellhead pressure, bar	NetP	Net power production, MWe
Q_{cond}	Rejected heat at the condenser, MWth	P_{aux}	power for auxiliaries, MWe

2. Simulation model

The simulation model is realized by means of a commercial process simulator [5]. 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 be 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 [2], 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 [6]. 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 [7]. The correlations by Beggs-Brill, Orkiszewski and HTFS 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.

2.2. Flash plant

In a conventional flash plant the geothermal fluid coming from wellhead is flashed, and separated steam enters a steam turbine, followed by a condenser. In conventional plants, 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.

At present, both the environmental concern and the sustainability issue by the reservoir exploitation require that the whole geothermal fluid flow is reinjected into the reservoir. It is to be stressed that no gaseous flow release is allowed, and CO_2 must be compressed up to a pressure suitable for mixing the CO_2 stream with the geothermal fluid prior to the reinjection process. Based on this statement, the plant scheme presented in Figure 1 was conceived: with respect to the conventional scheme extra components are added due to the requirement of CO_2 reinjection.

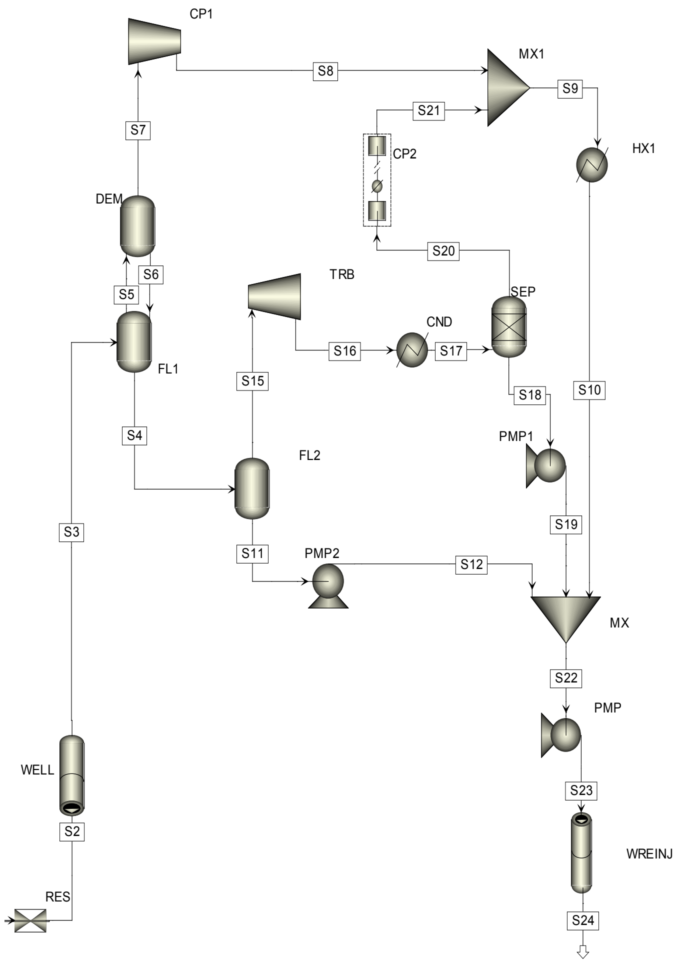

Figure 1 Total reinjection flash plant

The geothermal fluid coming from wellhead, which is a two phase mixture, undergoes a small pressure decrease (0.3-0.7 bar to obtain at least 98% of CO_2 separation) so that most of the CO_2 passes in the gaseous phase of the flow. After that, the mixture is cooled by means of an air cooler and 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 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 before the flash process requires the adoption of an extraction system at the condenser and of a further compressor.

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 this plant [2] in order to provide the highest possible electric power.

2.3. Binary (ORC) plant

Binary plants are usually selected when the geothermal fluid flow is in liquid phase. Though in some wells a satisfactory mass flow of geothermal fluid flows naturally at wellhead, in most of the wells a satisfactory mass flow is obtained only by means of artificial lift; a submersible down-hole pump is therefore commonly adopted. Two separate loops are distinguishable in the plant scheme represented in Figure 2: the geothermal loop and the power cycle. The downhole pump pressurizes the geothermal fluid so that it remains in the liquid phase and can be easily managed, together with the non-condensable gases possibly dissolved; a reinjection pump is also present in the scheme, as it may be required depending on the operating conditions.

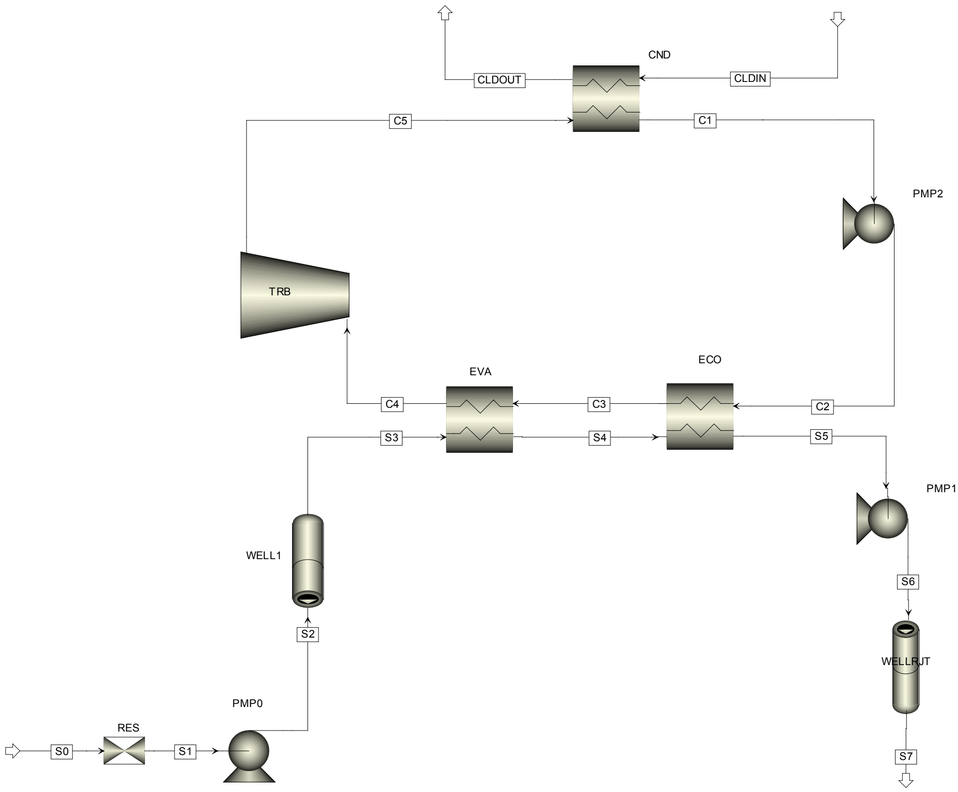

Figure 2 Binary plant

For the power cycle, the ORC technology, with simple saturated cycle, is selected, and considering the range of geothermal fluid temperatures for this study, HCFO-1233zd(E) [8] is proposed as working fluid. It is a new fluid with the similar property to R245fa in terms of critical pressure, critical temperature and molar mass. It has much lower GWP that R245fa and thus it is more environmentally friendly. The refrigerant HCFO-1233zd(E) (trans-1-chloro-3,3,3-trifluoropropene) is a liquid halogenated olefin. It is a non-flammable fluid with a critical temperature of about 166 °C, a critical pressure of about 37 bar and a normal boiling temperature of about 20 °C. According to preliminary investigation, it seems thermally stable at least up to nearly 200 °C. N-Pentane is also adopted in ORC application. However, it is an extremely flammable fluid which could increase the cost of ORC equipment due to safety issue. Thanks to a short atmospheric life (26 days), a low global warming potential (1-5 days) and a zero ozone depletion potential, HCFO-1233zd(E) is an environmentally friendly fluid. Prior to performance evaluation, it was checked that the library for the thermodynamic properties of fluids built in the simulator properly evaluates the properties of HCFO-1233zd(E) against experimental data [8] .

Adopting an integrated reservoir plant methodology, a “holistic approach [9]” must be selected for the binary plant, and an optimum mass flow rate must be found for the geothermal fluid flow. As a matter of fact, for the reservoir and well characteristic values selected in this work, the optimum flow lies beyond the maximum flow affordable by “state of the art” submersible pump (200 *l/s*) [10]; this limit mass flow value is therefore selected for the simulation of the binary plant. Once fixed the geothermal fluid flow, the plant main operating parameter remains the ORC evaporation pressure. A representation of the thermodynamic cycle with the two fluids is represented in Figure 3.

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
Air coolers specific electric consumption	0.02 $MW_e \cdot MW_{th}^{-1}$

The maximum pressures of the ORC plants are the ones that maximize the power production. For the ORC plants the condensing temperature is different for the two fluids: 1.6 bar for HCFO-1233zd(E) and 0.85 bar for n-Pentane. These implies that for a fixed maximum pressure the ratio of expansion for the turbine operating with n-Pentane is higher. However, the decreasing temperature are similar.

Performance evaluation is conducted for several values of reservoir temperature (150°C, 175°C and 200°C) and several values of CO_2 content (none, 1% and 5%). On the basis of the results obtained, the following statements can be done:

- Flash plant simulations: results show that the plant net power is strongly penalized by the CO_2 compressor consumption: as a limit case, for a reservoir temperature of 150°C, no net power generation is possible when the CO_2 reaches a certain content (5%).
- Binary plant simulations: the adoption of the new HCFO-1233zd(E) allows a slightly better performance with respect to the traditional n-pentane as ORC working fluid. The choice of the saturated cycle for this new working fluid may not be adequate at 200°C, since the pressure optimization curve has no maximum, and points towards always higher pressures. In some cases, when the CO_2 content increases, flash happen

in the formation, and geothermal fluid flow rate must be reduced at values lower than the assumed 200 l/s, so as to maintain everywhere single phase.

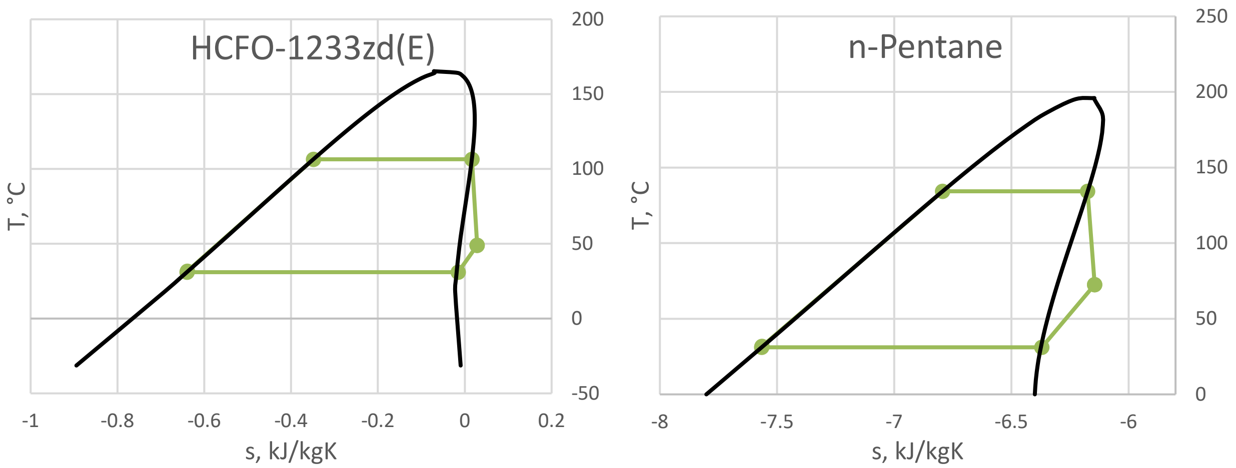

Figure 3 Thermodynamic cycle on T_s diagram for HCFO-1233zd(E) (left) and for n-Pentane (right) at maximum pressure of 12 bar

For a better description of the systems in Table 3and in Table 4 are reported the results for a reservoir at 200 °C containing different content of CO_2 for the flash plant and the binary plants respectively.

In Figure 5 are represented the results obtained with the two layouts, for ORC only the best case are reported. It can be noted that for the flash plant the amount of CO_2 affect the performance: when no CO_2 is present (case 0%) the performance is higher at all investigated temperature; increasing the amount of CO_2 can be positive. In fact, comparing the case containing 1% with respect to the case containing 5% of CO_2, the net power obtained with the latter it is higher because the pressure at the wellhead is higher and thus the temperature. These conditions permit a higher ratio of expansion in the turbine and a higher mass flow rate. The adoption of the pump in the binary cycles allows a larger well productivity than the natural one considered in the flash plant.

Table 3 characterization of flash-plants for the temperature of 200°C

CO_2 conc.	**0%**	**1%**	**5%**
p_{Wh}, **bar**	2.3	9.2	15.9
$\dot{m}_W$, **kg/s**	93	80	105
P_{aux}, MWe	0.74	5.4	2.6
Q_{cond}, MW_{th}	33.5	16.4	23.3
NetP, MWe	4.9	2.0	2.6

Table 4 characterization of binary plants HCFO-1233zd(E) at 200°C

	HCFO1233zd(E)		**n-Pentane**	
CO_2 conc.	**0%**	**1%**	**0%**	**1%**
$\dot{m}_{ORC}$, **kg/s**	547	384	220	210
$T_{max\ ORC}$, °C	153	153	130	130
$P_{max\ ORC}$, bar	29	29	11	11
Q_{cond}, MW_{th}	112	78.8	95.4	91.1
NetP, MWe	21.6	15.2	16.5	15.7

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 binary cycle, accomplished by means of an ORC cycle, may be a very profitable technical option even at high reservoir temperature, provided that a convenient submersible pump is employed. The effect of the CO_2 content on the plant performance is remarkable, and when it attains values close to 5%, the plant performance is greatly affected. As far as the flash technology is concerned, if total reinjection is required, the presence of CO_2 may drastically reduce the net power available, because of the power consumption for the reinjection process.

The good thermodynamic properties of the recently proposed ORC working fluid HCFO-1233zd(E) make the fluid a possible option for geothermal binary cycles.

With respect to the natural production of the geothermal fluid, the adoption of the submersible pump allows obtaining a larger amount of it. The ORC plant are equipped with this solution. As consequence, a larger net power than the flash-plant is obtained. Even if at higher CO_2 concentration, a pump cannot be used because of cavitation.

For the binary configurations, better results could be obtained with supercritical plant and with a recuperative layout. Modelling work will be validated against a geothermal site to get the trade-off solution from both thermodynamic and economic aspect.

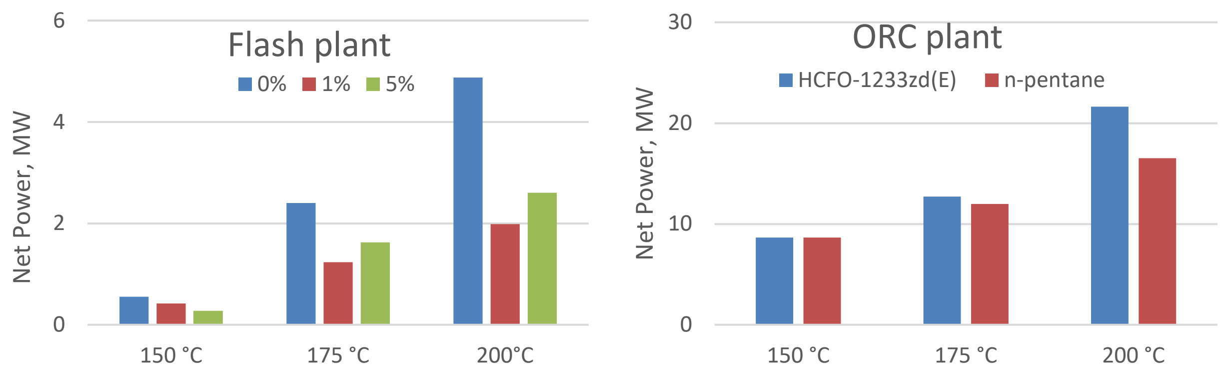

Figure 4 Performance evaluation comparison: (left) flash plants; (right) ORC plants

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