INTEGRATED ANALYSIS OF GEOTHERMAL RESERVOIR AND BINARY POWER CYCLE SYSTEM

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ABSTRACT

The binary power cycle technology with an organic Rankine cycle is suitable for the utilization of geothermal resources with low to medium temperatures (up to about 150 °C). In order to accurately predict the techno-economic viability of geothermal power plants, it is necessary to consider not only the organic Rankine cycle systems' performance parameters, but also the characteristics of the geothermal reservoir. In this paper an integrated analysis of the geothermal reservoir characteristics and binary power cycle system is presented, considering the degradation of the reservoir properties with time. Furthermore, a method to determine the techno-economically optimum value, represented by the minimum levelized cost of energy, of design power output of a binary power system for a given reservoir is proposed. The open source code Geothermal Reinjection Lifetime Prediction (GEOREPR) was used to predict the reservoir's lifetime taking into account both the reservoir characteristics and operational parameters, such as the injectivity index. The latter is a measure of the flow rate of the injected fluid at a given pressure. Alternations in the reservoir fluid density, its dynamic viscosity and salinity due to injection induced temperature changes were incorporated in the assessment of the geothermal brine mass flow rate. Two scenarios were considered for the binary power cycle system: (i) no degradation with time of the geothermal reservoir properties, and (ii) degradation of the geothermal reservoir properties due to progressive cooling of the geothermal reservoir and related changes in reservoir fluid density, dynamic viscosity and salinity. The results suggest that the levelized cost of electricity for a case with reservoir degradation is about 18 % – 19 % higher than that for the case with no degradation. For a given case study, the techno-economically optimum value of the design power output for the binary power cycle system is at year-11 considering a plant lifetime of 30 years.

1 INTRODUCTION

The use of geothermal heat for electricity generation has modestly grown at a rate of around 3.5 % annually, reaching a global installed capacity of approximately 15.96 GWe in 2021 (IRENA and IGA, 2023) and 16.13 GWe in 2022 (ThinkGeoEnergy, 2023). Nevertheless, geothermal energy still accounts for only 0.5 % of renewable-based installed capacity worldwide. Geothermal resource temperatures are divided into three groups: high ($T > 150$°C), medium (90-150°C), and low ($T < 90$ °C). High temperature geothermal resources are widely utilized for power generation. The binary power cycle technology with an organic Rankine cycle (ORC) is suitable for the utilization of geothermal resources with low to medium temperatures ($T \leq 150$ °C). The global installed capacity of geothermal energy powered ORC systems was more than 3 GWe in 2020 (Wieland *et al.*, 2021). However, the use of low to medium temperature geothermal resources for power generation is limited due to the high capital cost of the power plants.

The historical data of geothermal production wells demonstrates that most geothermal fields degrade naturally with time due to the intense extraction of reservoir fluid (Budisulistyo *et al.*, 2017). The

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degradation might take form of decreasing in volume (the so-called depletion) and/or in temperature of the geothermal fluid. The temperature and the volume of fluid present in the reservoir is commonly referred to as the heat source powering a geothermal plant. The thermodynamic and techno-economic performance of the organic Rankine cycle power system is affected by the variations in the geothermal fluid flow rates and temperatures during the lifetime of the plant (Gabbrielli, 2012). Thus, changes in the heat source are an important parameter to consider in the selection of the design power output. However, almost all previous works did not consider such degradations and used the initial thermodynamic properties of the geothermal heat resources when predicting the thermodynamic and techno-economic performance of the binary power cycle system (Budisulistyo *et al.*, 2017).

Sohel *et al.* (2011) investigated a new adaptive design of a geothermal plant, considering a combined cycle with the topping steam Rankine cycle powering a bottoming ORC system, to anticipate the change of the geothermal heat source characteristic. They provided four possible options for the combined cycle power plant depending on the changes in geothermal resource characteristics. The proposed adaptive designs increase the initial capital cost, however, they may result in benefits over the lifetime of the plant. Franco and Vaccaro (2012) presented a multidisciplinary approach considering the connections between the geological-geophysical and the binary power system aspects. Different scenarios for the geothermal resource exploitation were also analyzed to determine the temperature profiles at the production well over a period of time. Pamuji *et al.* (2016) used a curve fitting of the analytical expression for the reservoir temperature given by Axelsson et al. (2005) and performed an analysis by assuming (i) a decrease in the brine mass flow rate and temperature over life time, and (ii) an increase in the geothermal brine mass flow rate to compensate for the decrease in the heat input due to the decrease in the reservoir temperature. Based on the thermodynamic analysis using these assumptions, they reported that it is better to size the plant based on the end of well exploitation (30-year life) as design value (1.3 MWe) rather than the initial value (3.9 MWe). It is worth to mention that the initial temperature of the brine was 280 °C and a secondary circuit using Dowterm J thermal oil (with a maximum temperature of 150 °C) was used to power the ORC system. Also, it was assumed that the system is capable of allowing an increase in the geothermal brine mass flow rate from a minimum value of 57.11 kg/s to 162.28 kg/s during the 30-year period (including the geothermal brine to Dowterm J heat exchanger) to compensate for the variation in the decrease in the reservoir temperature.

Pollet *et al.* (2018) developed a simplified geothermal reservoir model and integrated that with a binary cycle power plant. The ORC power system was optimized considering three different steady-state conditions of the geothermal brine inlet temperature: (i) initial temperature of the geothermal reservoir (year 1, 149 °C), (ii) expected mid-life temperature of the geothermal reservoir (year 25, 129 °C), (iii) expected end of life reservoir temperature (year 50, 113 °C). They also compared the net power output of the plant for these three steady-state conditions (Case i: 332 GWh; Case ii: 241 GWh; Case iii: 171 GWh) with the transient conditions of the geothermal reservoir by maximizing the energy generated over the plant lifetime, while varying the evaporator pressure and the geothermal brine mass flow rate for a given ORC working fluid to geothermal brine mass flow rate ratio (Transient case: 168 GWh). An approach using the historical data of the existing geothermal reservoirs was adopted by Budisulistyo *et al.* (2017) for the lifetime design strategy for the binary geothermal plants. They considered the Wairakei geothermal resources in New Zealand and calculated the energy return on investment for four different cases based on the selection of the component sizes for the resource characteristics in the years 1, 7, 15, and 30. They reported that the optimum design point is at year 7 with an energy return on investment of 4.15, considering a 30-year lifetime of the plant and the other values of the energy return on investment were 4.07 for year 1, 3.27 for year 15, and 2.92 for year 30 design points. Recently, Hu *et al.* (2022) presented a concentrated solar power (using a parabolic trough collector system) retrofit option as a solution to the geothermal resource degradation. They investigated the off-design performance of the hybrid solar thermal and geothermal energy powered ORC system for a 30-year lifetime of the plant and reported that the retrofit year 6 is optimal. Of course, multiple retrofits further increase the net energy output from the plant, however, this is not cost-effective.

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In this paper we present an analysis of a geothermal energy powered binary power cycle system considering two scenarios: (i) no degradation in the available geothermal heat source, and (ii) degradation in the available geothermal heat source. The degradation was modelled by the Geothermal Reinjection Lifetime Prediction (GEOREPR) code, considering the changes in reservoir fluid density, dynamic viscosity and salinity. We also propose a method to determine techno- economically optimum values, represented by the minimum levelized cost of energy, of the design power output for the binary power cycle system for a given lifetime of the geothermal plant. The novel contributions of our work to state-of-the-art are as follows:

- A method to determine techno-economically optimum value of the design power output for a binary power cycle system for a given lifetime of the geothermal plant. The method includes consideration of alternations in the reservoir fluid density, dynamic viscosity and salinity due to injection induced temperature changes for the assessment of the geothermal brine mass flow rate.
- Quantification of the effect on the techno-economic performance of considering the degradation in the available geothermal heat source with time for a geothermal energy powered organic Rankine cycle system.

Section 2 presents the different models and methods for the analysis, while Section 3 describes the obtained results, and Section 4 presents the conclusions of the work.

2 METHODS

Geothermal heat sources are characterized by the reservoir properties, such as the temperature, and the porosity and permeability of the rocks. The last two determine the quantity of fluid available for extraction and the rate at which it flows into the well. The extraction (production) of geothermal fluid decreases the fluid volume in the reservoir, a process called reservoir depletion. It is commonly counteracted by the injecting water (brine) back into the geothermal reservoir. This often causes reservoir cooling since the injected water has much lower temperature than the reservoir itself. In addition, the fluid movement through the reservoir rocks might mobilize small grains/particles which can obstruct the pores, thus decreasing the quantity of geothermal fluid flowing into the well. All these processes lead to degradation of the heat sources, i.e. decrease in temperature and volume of the geothermal fluid.

2.1 Modelling of the heat source

As mentioned above, the water injected into to geothermal reservoir to counteract depletion is colder than the reservoir. The temperature difference is largest at the borehole wall where the injected water enters into the reservoir. However, the injected water warms up and mixes with the fluid (brine) already in place as it is moving through the reservoir. How fast the temperatures equilibrate depends on the volume and rate of injection, the rock permeability and the difference between the well and the reservoir pressures. The injectivity index I (kg/(s·bar)) is a measure of the flow rate (quantity per unit time) of the injected fluid at a given pressure.

The fluid flow (Q) through the reservoir is given by the Darcy equation:

$$Q = -\frac{kA}{\mu L}\Delta p \quad (1)$$

where k is the rock permeability, μ is the dynamic viscosity of the fluid, A is the cross-section area, L is the length (for example the distance between the injection and production wells), and Δp is the pressure difference.

Water/fluid density and viscosity depend on pressure, temperature and chemical composition. The density (ρ_{sw}) and dynamic viscosity (μ_{sw}) of the brine were calculated as follows:

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$$\rho_{sw}(T,S,p) = \rho(T) + K(T,S,p) \quad (2)$$

$$\mu_{sw}(T,S) = (1 + a(T)\cdot S + b(T)\cdot S^2)\cdot \mu_{pw}(T) \quad (3)$$

where T is the temperature, S is the salinity, p is the pressure, μ_{pw} is the dynamic viscosity of pure water, and a and b are parameters dependant on the temperature, which were calculated based on a procedure given in Belessiotis *et al.* (2016). The parameter $K(T,S,p)$ in the Eq. 2 was determined based on the procedure given in Sas (2022).

The mass flow rate variation over the time was calculated taking into account variations of density (ρ) and dynamic viscosity (μ) as a function of changes in temperature (T), pressure (p) and salinity (S) over time. The open source code Geothermal Reinjection Lifetime Prediction (GEOREPR, 2019) was used estimate the reservoir's lifetime taking into account both reservoir characteristics (temperature, pressure, porosity and permeability) and operational parameters, such as the injectivity index. An analysis of a geothermal energy powered binary cycle power plant was performed, considering degradation in the available geothermal heat source for the reservoir characteristics given in Table 1. The reported reservoir temperature, depth of the top reservoir, reservoir dimensions and injector-producer distance were used for the analysis. The fluid flow from the injector to the producer well (Eq. 1) is assumed to occur through a porous rock material (pipe) with a radius of about 4 m. The values of the input parameters used in the GEOREPR software are reported in Table 1.

2.2 Thermodynamic analysis

The ORC turbine design isentropic efficiency was determined as follows Astolfi and Macchi (2015):

$$\eta_{is,D} = \sum_{i=0}^{15} A_i \cdot F_i \quad (4)$$

where A_i are coefficients based on the number of stages of the ORC turbine, and F_i are parameters dependent on the volume ratio and the ORC turbine size parameter.

The ORC turbine power output at design condition ($\dot{P}_D$) was determined as follows:

$$\dot{P}_D = \dot{m}_D \cdot \Delta h_{is,D} \cdot \eta_{is,D} \quad (5)$$

where, $\dot{m}_D$ is the organic working fluid design mass flow rate, $\Delta h_{is,D}$ is the design isentropic specific enthalpy drop in the ORC turbine, and $\eta_{is,D}$ is the ORC turbine design isentropic efficiency.

Table 1: Values of the input parameters used in the GEOREPR software

Input parameters	Value
Earth's acceleration	9.81 m/s^2
Rock porosity	30 %
Rock permeability	10^{-12} m^2
Length of the reservoir	2000 m
Height of the reservoir	100 m
Width of the reservoir	10000 m
Reservoir temperature	215 °C
Brine density at room (20 °C) temperature	1043.196 kg/m^3
Viscosity of pure water @ 215 °C	1.249×10^{-4} Pa-s
Well length (from ground level to top reservoir)	1000 m
Distance injector-producer well	200 m
Initial mass flow rate	100 kg/s

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Table 2: Data required for thermodynamic analysis of the system

Input parameters	Value
Pressure drop in geothermal brine	300 kPa
Isentropic efficiency of the geothermal brine circulation pump and cooling water pump	0.75
Design efficiency of generator	0.93 (Haglind and Elmegaard, 2009)
Design efficiency of ORC turbine	Based on Astolfi and Macchi (2015)
Design isentropic efficiency of ORC feed pump	0.7 (Astolfi *et al.*, 2014)

The design gross electric power output of the plant ($\dot{P}_{gross,D}$) was determined as follows:

$$\dot{P}_{gross,D} = \dot{P}_D \cdot \eta_{mech} \cdot \eta_{gen,D} \tag{6}$$

where, η_{mech} and $\eta_{gen,D}$ are the design condition ORC mechanical and generator efficiencies, respectively. The input data required for the thermodynamic analysis of the geothermal energy powered plant are given in Table 2. For the given heat source temperature and mass flow rate at the design condition, the maximum operating temperature, and pinch point temperature difference for the evaporator and regenerator were optimized for the ORC power system based on the minimum levelized cost of energy.

Part load performance of the ORC power system was calculated as follows:

$$\left(\frac{\eta_{th,ORC,a}}{\eta_{th,ORC,nom}}\right) = a_0 + a_1 \cdot \left(\frac{\dot{Q}_a}{\dot{Q}_{nom}}\right) + a_2 \cdot \left(\frac{\dot{Q}_a}{\dot{Q}_{nom}}\right)^2 + a_3 \cdot \left(\frac{\dot{Q}_a}{\dot{Q}_{nom}}\right)^3 \tag{7}$$

where, $\eta_{th,ORC,a}$ is the actual thermal efficiency of the ORC system, $\eta_{th,ORC,nom}$ is the nominal thermal efficiency of the ORC system, $\dot{Q}_a$ is the actual thermal power input to the ORC system, and $\dot{Q}_{nom}$ is the nominal thermal power input to the ORC system. The correction factors for the deviation in the heat source temperature and cooling water temperature can be introduced in Eq. (7). The part-load efficiency parameters for the ORC power system can be calculated based on the detailed part-load modelling of each components (for example, Desai *et al.*, 2019) or based on the manufacture catalogues (for example, Turboden, 2018) or based on the actual plants' performance curves (for example NREL, 2018). In the present work, the part load efficiency parameters for the ORC power system were based on a curve fitting from the Turboden (2018) manufacture catalogue.

2.3 Economic analysis

The cost of the organic working fluid feed pump, ORC system's electrical generator and condenser was calculated as follows:

$$C = C_0 \cdot \left(\frac{Capacity}{Capacity_0}\right)^e \tag{8}$$

where, C_0 and $Capacity_0$ are the reference system's cost and capacity, and the exponent e is a scaling factor. The reference system cost and capacity were taken from literature (see Table 3).

The cost of the ORC turbine (C_T) was calculated as follows (Astolfi *et al.*, 2014):

$$C_T = C_0 \cdot \left(\frac{n}{n_0}\right)^{e_1} \cdot \left(\frac{SP}{SP_0}\right)^{e_2} \tag{9}$$

where, C_0, n_0 and SP_0 are the reference system's cost, number of ORC turbine stages, and ORC turbine size parameter, and the exponents e_1 and e_2 are scaling factors.

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The costs of the evaporator and regenerator were calculated as follows (Astolfi *et al.*, 2014):

$$C_{eva/reg} = C_0 \cdot \left(\frac{UA}{UA_0}\right)^e \cdot z \quad (10)$$

$$z = (10)^{(z_1 + z_2 \cdot \log p + z_3 \cdot log^2 p)} \quad (11)$$

where, C_0 and UA_0 are the reference system's cost and UA value, the exponent e is a scaling factor, and p is the pressure.
The annualized cost of the system (AC_{sys}) was calculated as follows:

$$AC_{sys} = \left(C_{sys} \cdot CRF + C_{O\&M}\right) \quad (12)$$

$$CRF = d \cdot \frac{(1+d)^n}{((1+d)^n) - 1} \quad (13)$$

where C_{sys} is total capital cost of the system (including the cost of the geothermal energy resource), CRF is capital recovery factor, $C_{O\&M}$ is annual operation and maintenance cost, d is the discount rate, and n is the lifetime of the plant. The input data required for the economic analysis of the geothermal energy powered plant are given in Table 3.

The levelized cost of electricity ($LCOE$) was calculated as follows:

$$LCOE = \frac{AC_{sys}}{E_{annual}} \quad (14)$$

where, E_{annual} is the net annual electricity generation.

Table 3: Data required for economic analysis of the system

Input parameters	Value
Cost of the geothermal energy resource	6,000,000 €
Cost of annual O&M	2 % of the total investment cost
Number of equivalent full load operation hours per year	8000 h
Cost parameters for ORC system's evaporator and regenerator	For evaporator: C_0 = 1570 k€, UA_0 = 4,000 kW/K, z_1 = 0.03881, z_2 = – 0.11272, z_3 = 0.08183, and e = 0.9 (Astolfi *et al.*, 2014); For regenerator: C_0 = 272 k€, UA_0 = 650 kW/K, z_1 = – 0.00164, z_2 = – 0.00627, z_3 = 0.0123, and e = 0.9 (Astolfi *et al.*, 2014)
Cost parameters for ORC system's turbine	C_0 = 1,287,810 €, n_0 = 2, SP_0 = 0.18 m, e_1 = 0.85 and e_2 = 1.1 (Astolfi *et al.*, 2014)
Electrical generator cost parameters	C_0 = 209,400 €, $Capacity_0$ = 5,000 kW_e and e = 0.67 (Astolfi *et al.*, 2014)
ORC system's gear box cost	40 % of the generator cost (Astolfi *et al.*, 2014)
Cost parameters for ORC system's condenser	C_0 = 13,075 €, $Capacity_0$ = 50 kW_{th} and e = 0.76 (Lemmens 2016)
Cost parameters for organic working fluid feed pump	C_0 = 14,658 €, $Capacity_0$ = 200 kW and e = 0.67 (Astolfi *et al.*, 2014)
Balance of ORC unit cost	40 % of the ORC unit's component costs (Astolfi *et al.*, 2014)
Discount rate	3 %
Lifetime of the plant	30 y

Note: All the parameters for the cost correlations have been converted using the CEPCI to the value of year 2023.

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2.4 Optimization of the design power output

The thermodynamic performance of the organic Rankine cycle power system is affected by the variations in the geothermal heat source during the lifetime of the plant due to the part load losses as shown in Fig. 1. Depending on the geothermal reservoir degradation, the geothermal plant's design and operating strategies, ORC systems part-load performance and the cost of the ORC power system components, there exists a techno-economically optimum value of the design power output (design condition capacity of the plant) leading to the minimum LCOE.

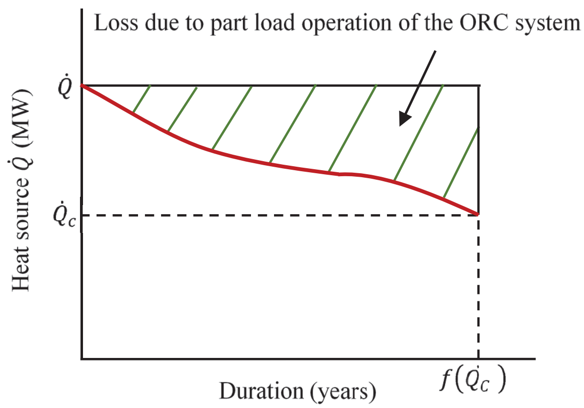

Figure 1: Variation of geothermal heat source ($\dot{Q}$) over time and the part load losses of the ORC power system (where, $\dot{Q}_c$ is the value of thermal power input from the heat source at the end of plant lifetime).

3 RESULTS AND DISCUSSION

In order to validate the model based on the GEOREPR code, the variation of mass flow rate over time (for 16 years) for the geothermal field in Miravalles, Costa Rica based on actual data reported in Monterrosa and Axelsson (2013) is compared with the prediction by the current model (see Fig. 2a). The results indicate that there is a good match between the model predictions and the actual data (a mean absolute percentage error of 7.7 %). Figure 2b shows the corresponding injectivity index over the time for the geothermal field in Miravalles, Costa Rica based on the prediction by the current model. It is worth to note that the predicted degradation of the geothermal heat source depends very strongly on the used reservoir characteristics. For example, the flow rate from the reservoir into the producer-well and from the injector to the producer well is determined (Eq. 1) by the assumed values of the parameters listed in Table 1. Geothermal reservoirs are located several hundreds to thousands meters below ground level, where rock properties, such as permeability, porosity etc. cannot be measured directly. Thus, there are considerable uncertainties in the assumed values, which are difficult to quantify. In addition, changes in permeability due to porosity reduction (compaction) and/or natural re-charge mechanisms (from rain water) of the geothermal reservoir were not included in the present analysis.

A model to predict the techno-economic performance of the binary power cycle system considering design and off-design conditions was developed. The design conditions code and calculation of the cost of the ORC power system is based on our previous work (Desai *et al.*, 2019). An analysis of a geothermal energy powered ORC plant was performed, considering degradation in the available geothermal heat source for given reservoir characteristics (see Table 1). The volume of the available geothermal fluid was estimated by multiplying the porosity and the reservoir volume. As a starting point, we assumed a mass flow rate of 100 kg/s and a 150 °C temperature of the geothermal brine. This heat source temperature is typical for exploration of medium temperature geothermal reservoirs, suitable for the binary cycle power plants, in Kenya. It is worth to note that more than 70 % of the geothermal resources available in the world are at temperatures under 150 °C (Franco and Vaccaro, 2012).

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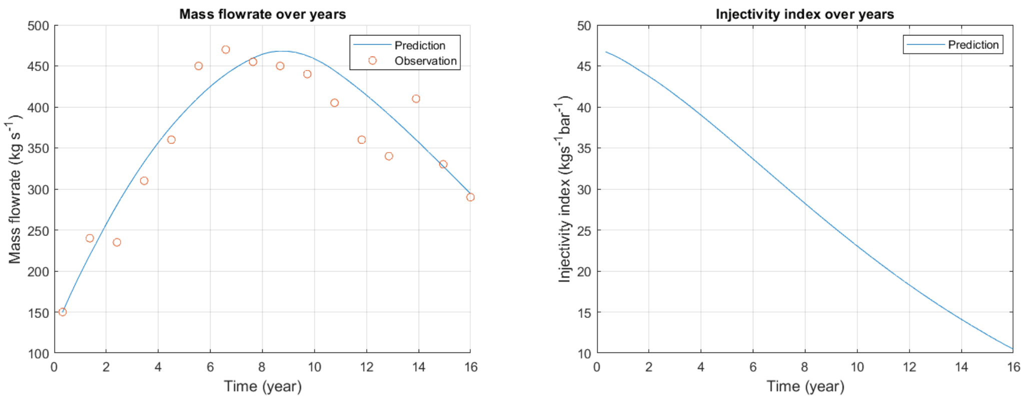

(a) (b)

Figure 2: (a) Variation of mass flow rate over the time for the geothermal field in Miravalles, Costa Rica based on the actual data reported in Monterrosa and Axelsson (2013) and the prediction by the current model. **(b)** Variation of injectivity index over the time for the geothermal field in Miravalles, Costa Rica based on the prediction by the current model.

In the case of no degradation, the heat source parameters were kept constant during the plant's lifetime. Three different ORC working fluids (R-245fa, R-1233zd(E), and n-pentane) were investigated for a given heat source. For a case of no degradation, based on the optimum techno-economic performance, the minimum LCOE is 0.0339 €/kWh for R-245fa, 0.0344 €/kWh for R-1233zd(E), and 0.0406 €/kWh for n-pentane. It is worth to note that R-245fa has a high global warming potential (GWP) of 1030 and a non-flammable R-1233zd(E) with ultra-low GWP (with GWP of 1) has an issue related to per- and polyfluoroalkyl substances (PFAS).

In the case with degradation, both the mass flow rate and the temperature of the geothermal brine were changed according to the equations given in section 2.1. The results suggest that the levelized cost of electricity for the case with degradation (using R-245fa as the ORC working fluid) in the available geothermal heat source (0.0402 €/kWh) is about 18.6 % higher than that of the case with no degradation in the available geothermal heat source (0.0339 €/kWh). This increase in the LCOE than that of the case with no degradation is about 18 % and 19 % for R-1233zd(E) and n-pentane working fluids, respectively. The increase in the LCOE is because the decline of the mass flow rate and temperature with time leads to a decrease in the net annual power output, and as a result, an increase in the levelized cost of electricity. This finding indicate that it is of crucial importance to conduct an integrated analysis considering both the power system part-load performance and reservoir degradation to estimate the techno-economic viability of a geothermal power system.

For the optimization of the design power output as described in section 2.4, two different ORC working fluids, R-245fa and R-1233zd(E), were considered. The techno-economically optimum design point, leading to minimum LCOE, is at year-11 for the presented case study considering a 30-year lifetime of the plant. It is worth noting that this optimum value is dependent on the geothermal resource degradation profile, the geothermal plant's design and operating strategies, ORC power system part-load performance parameters, and ORC power system cost. Therefore, it is not possible to generalize the optimum design point year for a geothermal power plant but rather it is necessary to perform such optimizations for a given heat source and the other mentioned parameters while designing and predicting the techno-economic performance of the plants.

It needs to be added that also the geothermal energy extraction strategy affects the lifetime of the reservoir. More aggressive extraction leads to a sharper decrease in the available resource. The part-

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load efficiency for the binary power cycle also decreases significantly at low loads. Therefore, also the overall operational and mitigation strategies (make-up wells, hybridization of the plant, and design modifications of the power cycles) of the plant play a vital role for the techno-economic viability of a geothermal power system.

4 CONCLUSIONS

In this paper, an integrated analysis of the geothermal reservoir and binary power cycle system was presented, considering the degradation of the geothermal heat source with time predicted using the modified Geothermal Reinjection Lifetime Prediction code. A method to determine the techno-economically optimum design power output of a binary power system for a given reservoir was also proposed. The results suggest that the levelized cost of electricity for the case with degradation in the available geothermal heat source is about 18 % – 19 % higher than that of the case with no degradation in the available geothermal heat source, suggesting that it is of crucial importance to conduct and an integrated analysis considering both the power system part-load performance and reservoir degradation to estimate the techno-economic viability of a given geothermal reservoir. For a given case study, the techno-economically optimum value of the design power output for the binary power cycle system is at year-11 considering a plant lifetime of 30 years. The present work provides the basis for further integrated analyses of geothermal plants optimizing the extraction rate for the geothermal resource and binary power plant capacity considering different plant operation and mitigation strategies (also including, for example, make-up wells, hybridization of the plant, and design modifications of the power cycles).

NOMENCLATURE

A	cross-section area (m^2)
AC	annualized capital cost (€/y)
C	cost (€)
CRF	capital recovery factor (y^{-1})
d	discount rate (%)
e	scaling factor as an exponent (-)
E	net annual electricity production (kWh_e/y)
η	efficiency (-)
I	injectivity index (kg/(s·bar))
k	rock permeability (m^2)
L	length (m)
$LCOE$	levelized cost of electricity (€/kWh_e)
μ	dynamic viscosity (Pa-s)
n	lifetime of the plant (y)
p	pressure (MPa)
$\dot{P}$	power (kW)
Q	fluid flow (m^3/s)
$\dot{Q}$	thermal power (kW)
ρ	density (kg/m^3)
S	salinity
SP	turbine size parameter (m)
T	temperature (K)

Subscript

a	actual
C	value at the end of plant lifetime
D	design
gen	generator

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is	isentropic
$mech$	mechanical
nom	nominal
out	outlet
pw	pure water
th	thermal

Abbreviations

GEOREPR	geothermal reinjection lifetime prediction
ORC	organic Rankine cycle

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