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Lifetime design strategy for binary geothermal plants considering degradation of geothermal resource productivity

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ABSTRACT

This work proposes a lifetime design strategy for binary geothermal plants which takes into account heat resource degradation. A model of the resource temperature and mass flow rate decline over a 30 year plant life is developed from a survey of data. The standard approach to optimise a basic subcritical cycle of *n*-pentane working fluid and select component sizes is used for the resource characteristics in years 1, 7, 15 and 30. The performances of the four plants designed for the different resource conditions are then simulated over the plant life to obtain the best lifetime design. The net present value and energy return on investment are selected as the measures of merit. The production history of a real geothermal well in the Taupo Volcanic Zone, New Zealand, is used as a case study for the lifetime design strategy.

The results indicate that the operational parameters (such as mass flow rate of *n*-pentane, inlet turbine pressure and air mass flow rate) and plant performance (net power output) decrease over the whole plant life. The best lifetime plant design was at year 7 with partly degraded conditions. This condition has the highest net present value at USD 6,894,615 and energy return on investment at 4.15. Detailed thermo-economic analysis was carried out with the aim of improving the plant performance to overcome the resource degradation in two ways: operational parameters adjustments and adaptable designs. The results shows that mass flow rates of *n*-pentane and air cooling should be adjusted to maintain the performance over the plant life. The plant design can also be adapted by installing a recuperator and reducing the heat transfer area of preheater and vaporizer.

1. Introduction

Renewable energy is of interest to reduce reliance on fossil fuels [1]. Geothermal energy is a promising power generation resource due to its consistency and reliability for a base load electricity supply. The geothermal resources are divided into two types according to production well enthalpy, steam-dominated and liquid-dominated resources [2]. Steam-dominated resources have been developed preferentially due to higher generation potential and the ability to use a simple condensing or back-pressure steam turbine. Liquid-dominated resources that were not considered economical have been increasingly utilized to generate the electricity by the application of binary organic Rankine cycle (ORC) [3].

The historical data of geothermal production wells demonstrates that most geothermal fields experience a decline in the temperature, pressure, enthalpy and/or flow as exploitation proceeds. This occurs in the Geyserardes geothermal field, California [4], Larderello-Valle Secolo area [5], and Wairakei geothermal reservoir [6]. The reinjection of the cooled brine has been suggested as contributing to temperature reduction of the resource, particularly over a long operational life and for the low temperature geothermal resources. The life cycle of a geothermal field is divided into four periods: (1) developing, (2) sustaining, (3) declining, and (4) renewable [7]. Geothermal power plants usually operate in off-design conditions over most of their operational life [8]. The attainable net power output over the whole plant life and the return on investment of the plant are influenced by the change of well charateristics during the well exploitation. The selection of the well charateristics (temperature and mass flow rate of brine) during plant design and optimization are very important because the selection of the parameters influence the plant size and the design variables. However, most researchers/designers of geothermal power plants use the initial thermodynamic properties (mass flow rate and temperature of the brine) of the geothermal resources for their calculation purposes and do not account for resource degradation.

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Nomenclature

ACC	air-cooled condenser
B	bare module factor
C	cost (USD)
D	percentage of flow decline rate (%)
E_c	energy for construction (TJ)
E_d	energy for decommission (TJ)
E_g	energy produced (TJ)
E_{op}	energy required for operation (TJ)
EDR	Exchanger Design & Rating
EROI	energy return on investment
F	factor
F_m	material factor
F_p	pressure factor
I	cost index
In	input
Old	base time
Out	output
ORC	organic rankine cycle
$\dot{m}$	mass flow rate (kg/s)
New	time when the cost is desired
N	equipment lifespan (year)
NPV	net present value (USD)
P	pressure (bar)
PEC	Purchase Equipment Cost (USD)
q	interest rate (%)
R	annual income (USD)
T	temperature (°C)
TCI	total capital investment (USD)
Tm	time (year)
TPC	total plant cost (USD)
TVZ	Taupo Volcanic Zone
W	the power of pump or radial turbine (kW)
W_{fans}	net power of fans (kW)
Wnet	net electrical power output (kW)
W_p	pump power (kW)
W_t	turbine power (kW)
Y_d	Stodola constant of the turbine ($m^{-2}\,s^{-2}\,°C^{-1}$)

Subcripts

1,2,3,...	state point in the system
BM	bare module
C	*critical*
cond	condenser
d	design point
ex	exit
geo	geothermal
GR	grassroots
in	inlet
m	material
max	maximum
n	number of main components
o	ambient condition
off	off-design
p	pressure
P	pump
T	turbine

Greek symbols

η	efficiency (%)
ρ	mass density (kg/m^3)
ϕ	mass flow coefficient, temperature form ($m\ s\ \sqrt{C}$)

Investigation of the ORC plants under off-design conditions and part loads has appeared in relatively few reported research investigations. Calise et al. [9] developed simulation models to evaluate the off-design performance of the ORC power plant utilizing the solar energy. The results of the off-design analyses show that mass flow rate of heat source is a key parameter in net power generation. Manente et al. [10] presented a detailed off-design ORC model in the geothermal fields to find the optimal operating parameters in response to changes of the ambient temperature and geofluid temperature. The results show that the power output is greatly influenced by the ambient temperature for the air cooling system and the geothermal inlet fluid temperature, mainly due to the influence on the cycle maximum pressure and the working fluid mass flow rate. Mines [11] investigated the influence of off-design operations on the performance of an air-cooled binary geothermal power plant. The results indicate that the power output are most sensitive to changing resource and ambient temperature. Fu et al. [12] investigated the effect of heat source flow rate on heat transfer characteristic and system performance of a 250-kW ORC plant. The results indicate that the performance of the system significantly increases with the increasing flow rate of heat source. Walnum et al. [13] focused on the off-design operation of Rankine cycles and compares the behaviour of transcritical CO_2 cycles and an ORC cycle with R-123 as working fluid. The main result shows that the ORC system is very sensitive to reduction in available heat, therefore it is reasonable to operate the ORC with some degrees superheat, to have a buffer.

Most of the off-design investigations reported in the geothermal literature above do not consider the geothermal resource degradation in designing and optimizing the binary plant designs. Gabbrielli [8] discussed the design strategy with the constant thermal input of the binary plant. However, none of them discusses the design strategy with the decrease of thermal input to the binary plant or investigates the best design point in relation to the range of thermodynamic properties over a geothermal resource lifetime. The design strategy is required to mitigate the performance reduction. Resource degradation causes off-design plant operation conditions over some or most of their operational life. The typical design process involves trade-offs between maximizing power output and minimizing capital cost of the plant. Thermodynamic and economic power plant design considerations should be investigated over the whole plant life to find the most profitable binary plant design for the developers and utility operators.

Most of the plant investigations on performance improvement reported in the literature do not consider adaptive main component designs due to resource degradation. Sohel et al. [14] analysed a new adapative design of the plant systems to anticipate the change of resource characteristic. The results provide four possible options of the hypothetical power plant depending on the changes in resource characteristics. The adapative designs affect the increase of the initial investment cost, but the total benefit may be greater over the life span of the plant. Pambudi et al. proposed the improvement of the existing geothermal power plants by modifying a single flash plant into a single flash combined with a binary system [15] and modifying a single flash plant into a double flash system [16]. The results reveal that the combined system with a binary plant and the double flash system increase the power output of the existing single flash plant at 17% and 20%, respectively.