



# Comprehensive analysis and parametric optimization of a CCP (combined cooling and power) system driven by geothermal source



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## ABSTRACT

A CCP (combined cooling and power) system, which integrated a flash-binary power generation system with a bottom combined cooling and power subsystem operating through the combination of an organic Rankine cycle and an ejector refrigeration cycle, was developed to utilize geothermal energy. Thermodynamic and exergoeconomic analyses were performed on the system. A performance indicator, namely the average levelized costs per unit of exergy products for the overall system, was developed to assess the exergoeconomic performance of the system. The effects of four key parameters including flash pressure, pinch point temperature difference in the vapor generator, inlet pressure and back pressure of the ORC turbine on the system performance were evaluated through a parametric analysis. Two single-objective optimizations were conducted to reach the maximum exergy efficiency and the minimum average levelized costs per unit of exergy products for the overall system, respectively. The optimization results implied that the most exergoeconomically effective system couldn't obtain the best system thermodynamic performance and vice versa. An exergy analysis based on the thermodynamic optimization result revealed that the biggest exergy destruction occurred in the vapor generator and the next two largest exergy destruction were respectively caused by the steam turbine and the flashing device.

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## 1. Introduction

The demand for energy is growing at an increasing rate due to the growth of population, and is arousing wide concerns about the security of energy supply for the long term [1]. Energy resources have been divided into three categories: fossil fuels, renewable resources and nuclear resources [2]. Using fossil fuels can result in environmental deterioration and resource depletion. Nuclear energy can cause serious problems for the environment and human health. Renewable energy sources, which are sustainable and environmental friendly, are hence under emerging exploitation [3]. Among all kinds of renewable energies, geothermal energy, which has abundant amount of storage [4] as well as significant base-load potential [1], is expected to make an increasing contribution for energy supply in a near future [5].

Variety of thermal systems have been developed to utilize geothermal energy. Conventional power systems that simply converted geothermal energy into electricity have been widely studied since 1904 when a dry-steam geothermal power system was first built and operated in the Tuscany region of Italy [6]. Although dry-steam power systems can utilize the dry geothermal steam directly to produce electricity, dry steam reservoirs are rare and only found in few fields around the world while most of the remaining conventional geothermal fields worldwide are wet fields [7]. Hence, more attention has been paid to other types of power systems including single-flash steam power systems, double-flash steam power systems, binary cycle power systems and flash-binary power systems to develop wet geothermal fields for power generation [8–12]. Particularly, for temperature of the geothermal water below 180 °C where direct flashing processes are not suitable anymore [13], ORC (organic Rankine cycle) and Kalina cycle, both of which are well proven and reliable technologies for energy conversion, especially for exploiting low-temperature heat sources, have been widely applied as the subsystem in binary cycle power systems [10–12,14–20]. However, conventional power plants can

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Nomenclature		$\rho$	density (kg/m <sup>3</sup> )
$A$	cross sectional area (m <sup>2</sup> ); heat exchanger area (m <sup>2</sup> )	$\mu$	viscosity (kg s <sup>-1</sup> m <sup>-1</sup> )
$Bo$	boiling number	<i>Subscripts</i>	
$\dot{C}$	cost rates (\$ year <sup>-1</sup> )	A	upper part
$\dot{C}_{dif}$	fictitious cost rates associated with dissipative components (\$ year <sup>-1</sup> )	B	lower part
<i>CEPCI</i>	chemical engineering plant cost index	BM	bare module
<i>CRF</i>	capital recovery factor	cond	condenser
$c$	levelized costs per unit of exergy (\$ (MWh) <sup>-1</sup> )	cond1	condenser 1
$c_p$	specific heat (J kg <sup>-1</sup> K <sup>-1</sup> )	cond2	condenser 2
$D$	diameter (m)	D	destruction
$\dot{E}$	annual exergy transfer rates (J year <sup>-1</sup> )	elec	electricity
$\dot{E}_x$	exergy flow rates (J s <sup>-1</sup> )	es	equivalent diameter
$ex$	specific exergy (J kg <sup>-1</sup> )	evap	evaporator
$F$	factor	ex	exergy
$f$	friction factor	F	fuel
$G$	mass velocity (kg m <sup>-2</sup> s <sup>-1</sup> )	he	heat exchanger
$h$	enthalpy (J kg <sup>-1</sup> ); convection heat transfer coefficient (W m <sup>-2</sup> K <sup>-1</sup> )	$i,j,k$	state points
$i_{eff}$	effective discount (%)	i	inside
$K$	constant	in	inlet
$L$	length (m)	ip	inlet pipe
$l_B$	baffle spacing (m)	L	loss
$\dot{M}$	mass flow rates (kg s <sup>-1</sup> )	l	liquid
$N$	number of the tubes	M	material factor
$n$	lifetime (year)	m	mean
$Nu$	Nusselt number	max	maximum
$P$	pressure (bar)	min	minimum
$Pr$	Prandtl number	o	outside
$P_t$	distance between tubes (m)	out	outlet
$Q_{vs}$	volumetric stream flow (m <sup>3</sup> s <sup>-1</sup> )	P	product; pressure factor
$\dot{Q}$	heat transfer rate (W)	pump	pump
$q_m$	average imposed wall heat flux (W m <sup>-2</sup> )	pump1	pump 1
$Re$	Reynolds number	pump2	pump 2
$r$	enthalpy of vaporization (J kg <sup>-1</sup> )	q	heat transfer; cold exergy output
$s$	specific entropy (J kg <sup>-1</sup> K <sup>-1</sup> )	ref	reference period
$T$	temperature (K)	s	single-phase
$t$	working hours (hours)	ss	shell-side
$U$	overall heat transfer coefficient (W m <sup>-2</sup> K <sup>-1</sup> )	sep	separator
$V$	volume (m <sup>3</sup> )	system	exergy products produced by the overall system
$v_t$	terminal velocity (m s <sup>-1</sup> )	th	thermal
$\dot{W}$	power (W)	tot	total
$x$	vapor quality	ts	tube-side
$y$	exergy destruction ratio (%)	turb	turbine
$\dot{Z}$	annually levelized cost value (\$ year <sup>-1</sup> )	turb1	steam turbine
<i>Greek letters</i>		turb2	ORC turbine
$\delta$	thickness (m)	v	vapor
$\Delta t_m$	logarithmic mean temperature difference between hot side and cold side (K)	vg	vapor generator
$\epsilon$	component exergy efficiency (%)	w	power
$\eta$	efficiency (%)	well	drilling wells
$\lambda$	thermal conductivity (W m <sup>-1</sup> k <sup>-1</sup> )	wt1	power produced by steam turbine
		wt2	power produced by ORC turbine
		y	per year
		0	ambient state
		1–23	state points

only produce electricity and are not adequate for meeting with diverse consumers' requirements for energy supply. To satisfy the diverse users' demands and to utilize the energy source more efficiently, some cogeneration systems that combines electricity generation with other kinds of energy production have been

developed for the exploiting of low- or medium-temperature heat sources such as geothermal water. A number of studies on geothermal cogeneration systems have been concentrated on the CHP (combined heat and power) technologies, which are relatively mature technologies directly using the geothermal water

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