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Research Paper

Techno-economic assessment for the integration into a multi-product plant based on cascade utilization of geothermal energy

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HIGHLIGHTS

- Cascade utilization of low- and mid-temperature geothermal energy is presented.
- The system consists of three thermal levels producing power, ice and useful heat.
- A techno-economic analysis is performed evaluating energy and economic benefits.
- A simple optimization algorithm was developed to optimize system benefits.
- Inconvenience of low thermal efficiency and high capital cost of ORC were overcome.

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ABSTRACT

The Organic Rankine Cycle (ORC) is a technology that has reached maturity in cogeneration or waste heat applications. However, due to low thermal efficiency and high capital cost of ORC machines, geothermal-based ORC applications represent only a small percent sharing of the geothermal power capacity worldwide. Several countries have reported a great potential of low- and mid-temperature geothermal energy, representing an opportunity to explore a more efficient ORC integration into non-conventional applications of geothermal energy. One alternative, resembling the polygeneration concept, is known as cascade utilization of geothermal energy, where different energy outputs or products can be obtained at the same time, while improving thermal and economic performance. In this paper, a techno-economic analysis for the selection of small capacity ORC machines and absorption chillers (for ice production), to be integrated into a polygeneration plant that makes use of geothermal energy in a cascade arrangement, is presented. A simple cascade system that consists of three sequential thermal levels, producing simultaneously power, ice and useful heat is proposed, considering typical temperatures of geothermal zones in Mexico. A simple optimization algorithm, based on energy and economic models, including binary variables and manufacturer's data, was developed to evaluate and determine optimal ORC and absorption chiller units. Results show, firstly, that inconvenience of low thermal efficiency and high capital cost of ORC machines can be overcome. Secondly, that the temperature difference in ORC evaporator strongly influences the overall energy efficiency and the economic profit of the system.

1. Introduction

Renewable energy sources have significantly become a reality as an alternative to the use of fossil resources and for the reduction of associated adverse effects. The technological and sustainable development of this type of energy can contribute to alleviate the world's energy need. In this regard, a renewable energy that stands out, due to its potential reserves and technological maturity is geothermal energy [1]. Geothermal resources of high-enthalpy (temperatures higher than 150 °C) have been widely exploited to generate electricity. On the contrary, and despite of the great potential estimated worldwide, resources of low- and medium-enthalpy (less than 100 °C for low temperature and 100–150 °C for medium temperature) have been used in a lower proportion for power generation. This can be attributed to high investment costs and the low thermal efficiency of associated energy

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Nomenclature

CF	cash flow, USD
C_{LAT}	latent heat, kJ/kg
COP	coefficient of performance
C_p	specific heat capacity, kJ/kg K
C_{OM}	operating & maintenance cost, USD
EG_{H2O}	expenses for potable water purchased, USD
EQ_{UDU}	thermal energy for direct use, kW h
EW	electrical energy, kW h
f_{dt}	dead time factor for ice production
I	investment cost, USD
i	interest rate, %
IN	income, USD
L	depth, m
$\dot{M}$	mass flow rate, kg/s
M	mass, kg
N	lifetime, years
NPV	net present value, USD
$\dot{Q}$	heat rate, kW
T	temperature, °C
t_{op}	annual operating time, h
UC	unit cost, USD
$\dot{W}$	power, kW
ε	effectiveness
η	efficiency, %
ρ	density, kg/m^3

Subscripts

ADU	available heat for direct use
ANNUAL	yearly quantity or amount
COOL	cooling
CC	cooling chamber
E	electrical
EL	electricity
FR	freezing
GEO	geothermal
HW	hot water
ICE	ice for human consumption
ORC	Organic Rankine Cycle
TAR	thermally activated refrigeration
TOT	total
UDU	useful heat for direct use
W	water
WELL	geothermal well

conversion technologies such as binary cycle, Kalina Cycle or Organic Rankine Cycle (ORC) [2,3]. Additionally, it is interesting to note that medium-enthalpy geothermal energy is effectively used in direct applications for heating and cooling processes, producing about three times more revenue than geothermal power applications [4,5].

The use of geothermal energy through a novel concept named cascade utilization or cascade use has been proposed as a measure to spread the use of low- and mid-enthalpy resources for electricity production and direct utilization. Utilization of geothermal energy in a cascade manner is an effective arrangement to utilize thermal energy at different temperature levels, obtaining different products, increasing the overall efficiency and lowering production costs of the combined system [6–9]. Cascade utilization can be seen as a particular case of integrated energy systems, which also appears under the name of polygeneration systems, focusing on the principle of using one or more energy resources to obtain various products more efficiently than conventional systems [6].

The cascade utilization method has been the subject of current studies, focusing on how the system should be integrated, designed and improved. Jin et al. [6] have introduced the principle of cascade utilization of both chemical and physical energy, investigating a polygeneration system for power and methanol production. This study indicated that cascade utilization provides superior performance and improved energy saving. Arslan and Kose [10] conducted a feasibility study of installing a small-scale geothermal plant combined heating and balneology. The system was optimized using energy, exergy and life cycle cost analysis, showing that cascade utilization is more economically attractive. Kodhelaj et al. [11] proposed a demonstrative geothermal center with cascade use coupled solar panels. In this study, an economic analysis was carried out, showing that the hybrid system is completely competitive. Ratlamwala et al. [12] carried out an energy and exergy analysis of a system consisting of a binary cycle power unit and a quadruple effect absorption unit producing cooling, heating, power and hot water. The study highlighted environmental and efficiency improvements.

Li et al. [13] presented a new compound system combining an ORC unit with a gathering heat tracing station and an oil recovery system. Defining an objective function that reflected both technical and economic performances, the system was optimized to reach profitability. Fu et al. [14,15] proposed a cascade system with a Kalina cycle integrated to an oil production process to recover heat and purify crude oil from a geothermal fluid. An exergy analysis was carried out to determine the operating conditions with the lowest exergy destroyed. The payback period was also reduced through this approach. The same authors [15] presented a comparison of energy and economic performance of an ORC and a Kalina cycle integrated to an oil production process, being the Kalina cycle superior in performance due to its higher power output for the same conditions. Jiang et al. [16] proposed a novel type of cascading cycle integrating an ORC at the first level for power generation and an adsorption cycle at the second level for freezing. Jianǵs analysis indicated that exergy efficiency was improved, being desirable to have a large temperature drop in the overall conversion system. Finally, Luo et al. [17] investigated an integrated cascade utilization system powered with waste geothermal water from an existing flash power plant. After power generation, the geothermal fluid was utilized for cooling, agricultural product drying and residential bathing. Various potential schemes were proposed and the optimal scheme was developed through optimization.

The previous investigations highlight the viability of using geothermal energy through an innovative arrangement called cascade utilization. It can be seen that several applications have been proposed and the viability depends on what components or devices are integrated and how the integrated systems are designed and evaluated to achieve optimal energy and economic performance. Additionally, thermally activated devices, such as ORC and absorption machines, are designed to make use of low-grade temperature sources. However, they have an inherent low thermal performance along with higher costs, sometimes prohibited for certain applications. Manufacturers offer a wide variety of components with different characteristics that also might affect the final configuration of cascade systems.

The goal of this study reported in this paper is to overcome the limitations of low thermal efficiency and high capital cost of thermally activated components, developing a procedure for the selection of small capacity ORC machines and absorption refrigerators to be integrated into a polygeneration plant, that makes use of geothermal energy in a cascade arrangement. The study was con-