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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.

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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 conducted considering the particular situation of Mexico, where there are 276 reported locations with geothermal manifestations with 110 °C as the average temperature, able to be sustainably exploited through this innovative method [18]. The authors of this study have conducted a prefeasibility study to analyze configurations of a multi-product system formed by three temperature levels producing sequentially, power, ice for human consumption and heating for direct uses. It was found that the Mexican geothermal resources and the economic conditions of the country are suitable for small applications of cascade utilization of geothermal energy [19]. The system analyzed is a geothermal cascade system composed by three thermal levels. The paper is organized according to the following sections: Section 1, Introduction; Section 2, contains procedures for conducting the techno-economic assessment, including a simple optimization implementation for component selection. Section 3 includes a discussion of the results; and Section 4 is devoted to the conclusions.

2. Techno-economic assessment procedure

In this section, the procedure followed to carry out the techno-economic assessment of the multi-product plant with cascade utilization of geothermal energy is presented. A description of the cascade system for the study, including the assumptions and main considerations, is presented. Features of the ORC machines, absorption chillers and direct uses that can be integrated into the cascade system are also provided. Finally, details about energy and economic modeling and its implementation are described.

2.1. Description of the cascade system

The cascade system under study includes three thermal levels (with one main component or device per level), producing simultaneously and sequentially: power, ice for human consumption and useful heat for a further direct use. The component of the first level is an ORC machine with an absorption chiller to be used in the second level. Finally, a heat exchanger is the component to be included in the last level of the geothermal cascade. The main heat source for the system considers the availability of low- and mid-temperature geothermal resources. Fig. 1 shows the conceptual three-level cascade system.

2.2. Assumptions and main considerations

The main assumptions for each thermal level forming the cascade system are given below:

- *Thermal Level 1.* Geothermal hot water coming from a geothermal well, provides heat to the first component of the cascade, i.e. the ORC. The temperature of the available geothermal hot water is considered in a range from 80 to 130 °C, representing most of the thermal manifestation of low- and mid-enthalpy of Mexican geothermal resources [18]. The temperature difference for the heat exchange process within the ORC evaporator is considered according to the design conditions of ORC machines commercially available. Therefore, the outlet temperature available to operate thermal level 2 will depend on this value.
- *Thermal Level 2.* Once the geothermal hot water leaves the ORC machine at the Thermal Level 1, geothermal water is ready to enter the second thermal level of the cascade system. In this second level, a thermally activated refrigeration machine (TAR) is placed to produce ice. As this study considers ice production for human consumption, the machines to be included are the ones able to cool down to 0 °C or below. The hot water leaving the TAR has sufficient temperature to feed the next level of the cascade (between 70 and 90 °C) depending on the initial temperature of the geothermal resource and the temperature reduction in the Thermal level 1 and 2.
- *Thermal Level 3.* The last level of the cascade is formed once the hot water leaves the TAR component. As is expected to have a temperature between 70 and 90 °C, hot water has the energy content and temperature to match a wide variety of geothermal direct uses. For this level, the hot water coming from the TAR is directed to a heat exchanger with a thermal effectiveness of 70 percent. Finally, the hot water leaving the heat exchanger is reinjected back to the geothermal reservoir.

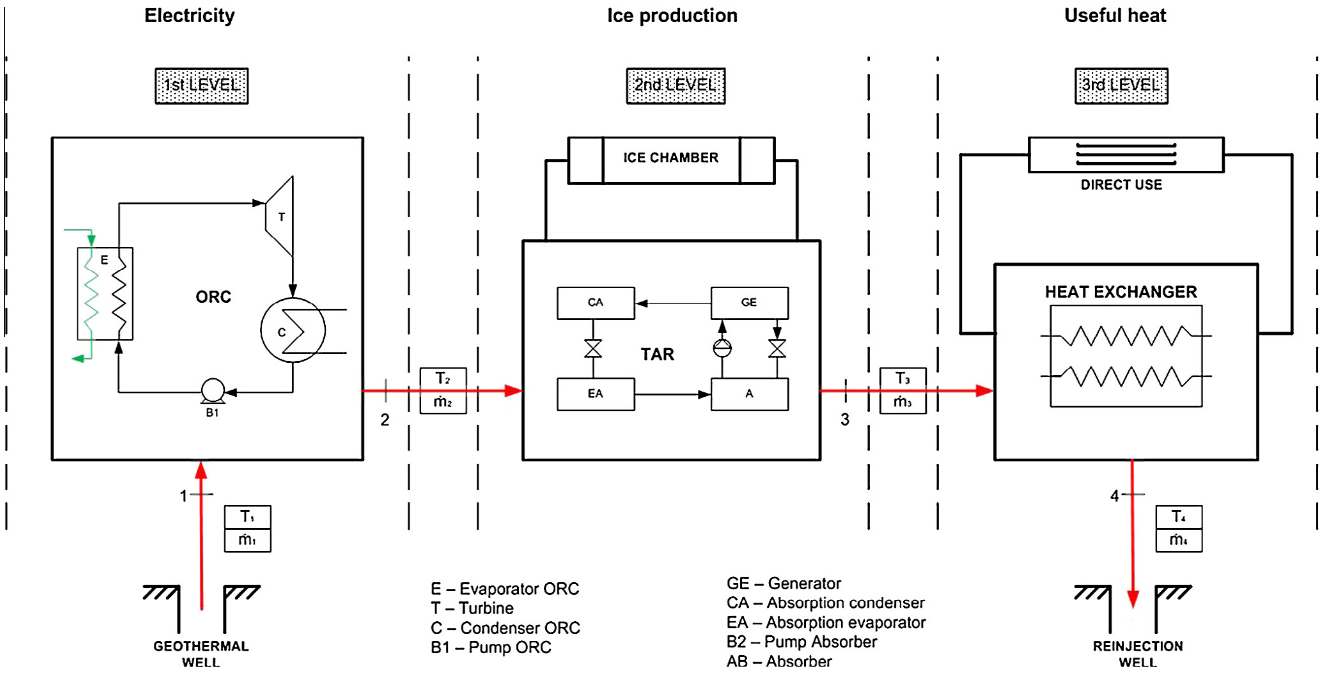

Fig. 1. Conceptual schematic of a three-level cascade system.

Table 1
ORC machines considered in the techno-economic analysis.

Code	Model	W_{ORC} [kW]	T_{ORC} [°C]	ΔT_{ORC} [°C]	η [%]	I_{ORC} [USD]
ORC01	IT10	11.0	95.0	25.1	6.1	$52,356.38
ORC02	PMTH-25	25.0	95.0	7.0	7.8	$99,983.62
ORC03	4200	35.0	104.0	25.9	7.0	$247,263.00
ORC04	IT50	55.0	95.0	19.8	9.9	$186,104.96
ORC05	4400	65.0	116.0	16.9	7.6	$292,038.00
ORC06	IT100	109.9	95.0	19.9	9.9	$321,113.32
ORC07	6500	110.0	116.0	14.6	8.5	$409,159.00
ORC08	125XLT	125.0	95.0	16.3	8.9	$355,399.84
ORC09	MT	125.0	121.0	21.2	9.1	$355,399.84
ORC10	WHG 125	125.0	109.4	10.5	10.6	$355,399.84
ORC11	OPB-150	155.0	135.0	21.2	9.1	$496,930.00
ORC12	IT250	274.7	95.0	19.9	9.8	$660,956.33
ORC13	280	280.0	91.0	16.3	8.9	$655,000.00

2.3. Main components and characteristics

2.3.1. Organic Rankine Cycle

Many researchers have studied ORC as the primary option to exploit, in a sustainable way, low- and medium-temperature geothermal sources for power generation [20,21]. This type of power cycles can operate at design conditions, with hot water at temperatures higher than 90 °C, even some ORC machines can operate at part load with temperatures as low as 77 °C, providing more flexibility to be integrated. Manufacturers offer small energy conversion systems of standardized sizes with nominal power output ranging from 10 to 1000 kWe. However, a notorious difference exists in thermal efficiency, temperature of activation and capital cost, requiring a careful selection for a given application [22]. The cascade system of this study is intended for small applications, limiting the ORC power output up to 300 kWe. A survey was conducted to identify ORC manufacturers and machines commercially available. Table 1 includes ORC machines with different power outputs between 11 and 280 kWe. Table 1 includes only input parameters to conduct the techno-economic analysis, such as nominal power, temperature of activation, temperature difference in the evaporator, thermal efficiency and capital cost (commercial brand was omitted, including only models). In order to identify ORC machines for the selection procedure, each ORC was designated with a simple code.

It is worth noting that the aim of this work is not the design of ORC units, therefore aspects such as optimal selection of the working fluid, brine chemistry, design of individual components of the ORC, etc., were not considered. As previously mentioned, only ORC units of small and medium capacity were included, because for small applications is easier to match the heat requirement of other components at the different thermal levels [9].

2.3.2. Absorption chillers

Regarding thermally activated machines, the components considered were single-effect and half-effect (or double-lift) absorption machines able to produce ice and reach a temperature of -13 °C for ice storage in cold chambers. The temperature of activation of this technology mainly depends on the working fluid and number of absorption effects. Usually, the higher the number of effects, the higher the temperature of activation. According to the expected thermal levels defined for the study, two different machines were considered:

- NH_3-H_2O single-effect absorption chillers with a typical activation temperature of 90 °C, a nominal coefficient of performance (COP) of 0.6 and a temperature difference in the generator of 10 °C.
- NH_3-H_2O half-effect absorption chillers with a typical activation temperature of 80 °C, a nominal COP of 0.3 and a temperature difference in the generator of 10 °C.

2.3.3. Direct uses

Direct uses of low- and mid-temperature geothermal energy in applications for heating and cooling processes are reported to provide three times more revenue than stand-alone geothermal power applications [4,5]. There is a wide variety of direct use applications with temperatures ranging from 30 to 80 °C having in common the use of a heat exchanger. In this study, a final use is not specified but fruit dehydration or greenhouses are good candidates. For simplicity, a heat exchanger with a thermal effectiveness of 70 percent was considered in the last thermal level.

2.4. Energy modeling

Equations to model main components of geothermal cascade system are based on mass, energy balances and energy conversion parameters, such as energy efficiency, COP, and thermal effectiveness of the ORC, TAR and heat exchangers, respectively. In this study, once the nominal power of the ORC unit is pre-established (from Table 1), the activation heat rate required by the ORC unit for power production can be obtained by means of Eq. (1):

$$\dot{Q}_{ORC} = \frac{\dot{W}_E}{\eta_{ORC}} \tag{1}$$

The mass flow rate of geothermal hot water can determined according to:

$$\dot{M}_{GEO} = \frac{\dot{Q}_{ORC}}{Cp_w(T_1 - T_2)} \tag{2}$$

The heat input for the absorption machine can be determined using the mass flow rate of the geothermal hot water and the temperature drop in the absorption machine generator, by means of Eq. (3):

$$\dot{Q}_{TAR} = \dot{M}_{GEO} Cp_w (T_2 - T_3) \tag{3}$$

As the cooling capacity of the TAR component and the heat input are related through the COP, the cooling heat rate can be determined by the following expression:

$$\dot{Q}_{COOL} = COP_{TAR} \cdot \dot{Q}_{TAR} \tag{4}$$

The load $\dot{Q}_{COOL}$ is dedicated to cover both ice and cooling chamber loads, $\dot{Q}_{ICE}$ and $\dot{Q}_{CC}$, respectively. A 50 percent of the total cooling capacity ($\dot{Q}_{COOL}$) was allocated for ice storage capacity ($\dot{Q}_{CC}$), the remaining available load to produce ice was calculated by means of Eq. (5). The amount of ice produced was then calculated by Eq. (6) and it depends on the temperature drop to cool down fresh water from the ambient temperature (T_w) to the freezing temperature (T_{FR}), and from the freezing temperature to the necessary temperature for storing the ice produced. Eq. (6) includes a factor f_{dt}, to consider dead times between ice production cycles. This factor reflects that ice is produced in batches and loading, cooling, harvesting and storage times reduce the effective running time of the icemaker [23]. In this study, a load of 50 percent of the total cooling capacity was defined for $\dot{Q}_{CC}$. A f_{dt} value of 0.5 for the dead time between ice production cycles was assumed.

$$\dot{Q}_{ICE} = \dot{Q}_{COOL} - \dot{Q}_{CC} \tag{5}$$

$$\dot{M}_{ICE} = \frac{\dot{Q}_{ICE} \cdot f_{dt}}{Cp_w(T_w - T_{FR}) + C_{LAT} + Cp_{ICE}(T_{FR} - T_{ICE})} \tag{6}$$

For the third level of the cascade system, the heat available for direct uses (ADU) and useful heat for direct uses (UDU) applications was estimated by means of Eqs. (7) and (8). Typical temperature differences of heat exchangers for dehydration, greenhouses or other direct uses, are in the range from 10 to 20 °C [24]. Based on this, a value of 10 °C was considered in the study.

$$\dot{Q}_{ADU} = \dot{M}_{GEO} \cdot Cp_w(T_3 - T_4) \tag{7}$$

$$\dot{Q}_{UDU} = \varepsilon_{UDU} \cdot \dot{Q}_{ADU} \tag{8}$$

Thus, considering an initial temperature (T_1) of the geothermal hot water at the first level of the cascade system and the temperature (T_4) at the last level, the total amount of geothermal heat input to the system can be estimated by:

$$\dot{Q}_{GEO} = \dot{M}_{GEO} \cdot Cp_w(T_1 - T_4) \tag{9}$$

Finally, the net energy performance of the cascade system can be obtained by considering the three outputs produced by the cascade system (power, ice and useful heat) as well as the energy input delivered to obtain these three products, using Eq. (10):

$$\eta_{GEO} = \frac{\dot{W}_E + \dot{Q}_{COOL} + \dot{Q}_{UDU}}{\dot{Q}_{GEO}} \tag{10}$$

2.5. Economic modeling

Additionally, an economic model was developed to determine the profitability of the geothermal cascade system. By coupling the energy and economic model, it is possible to estimate the techno-economic feasibility of the entire system. There are several economic indicators to estimate the economic behavior of a certain investment project, but the most utilized indicator is the net present value (NPV). In order to determine the NPV, it is necessary to estimate capital costs, expenses, incomes and operating and maintenance (O&M) costs. Capital costs represent the first outcome related to acquisition, construction, installation and commissioning of the system. For the geothermal cascade system studied here, such expenditures include drilling, purchase of main components (ORC, TAR, and heat exchanger), subsystems, piping, etc.

The capital cost associated to drilling can be estimated as a function of drilling depth with a simple expression given by Eq. (11) [25]. According to previous studies of several Mexican geothermal reservoirs, geothermal hot water at the temperature assumed in this work, is available drilling a depth in the range between 200 and 300 m [18]. For this study, a geothermal well with 300 m depth was considered.

$$I_{WELL} = 2150\left[\frac{\$}{\text{m}}\right] \cdot L_{WELL} \tag{11}$$

In order to estimate the investment cost of the ORC and absorption machines, information from different sources was gathered about the cost of these two components. From the information collected, two linear equations as a function of nominal power output of the ORC and cooling capacity of the TAR were obtained by linear curve fitting; see Eqs. (12) and (13), respectively:

$$I_{ORC} = 1229.8\left[\frac{\$}{\text{kW}}\right] \cdot \dot{W}_E + 352327[\$] \tag{12}$$

$$I_{TAR} = 952.3\left[\frac{\$}{\text{kW}}\right] \cdot \dot{Q}_{COOL} + 159258[\$] \tag{13}$$

The total capital cost for the cascade system was obtained as the sum of the individual capital cost of the geothermal well, the ORC and the TAR, as well as other additional costs related to the purchase of heat exchangers and other subsystems. Based on other reported cases, it was assumed a 25 percent more of the capital cost to cover the additional subsystems [26]. Therefore, the total investment cost of the geothermal cascade system is given by:

$$I_{TOT} = 1.25 \cdot (I_{WELL} + I_{ORC} + I_{TAR}) \tag{14}$$

The total investment must be annualized including the expected lifetime of the system and the interest rate to take into account the time value of money. The annual investment cost can be obtained using Eq. (15). For this study, an interest rate of 10 percent and a lifetime of 20 years were considered.

$$I_{ANNUAL} = I_{TOT}\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \tag{15}$$

The products of the geothermal cascade system represent an opportunity for economic profit. It is possible to have revenues from power trading and by selling ice and thermal energy. In order to estimate these incomes, as the economic analysis was performed on an annual basis, it is necessary to determine the annual amounts of electric energy, ice and thermal energy produced and their corresponding incomes.

The total annual electricity generated was estimated using Eq. (16). An equipment availability factor of 85 percent was assumed, giving 7446 h of effective operating time (t_{op}) throughout the year. Expected revenues from electricity trade were calculated using Eq. (17). Given that in Mexico it is not allowed to directly sell electricity and only internal trade is permitted between industries through a partnership agreement, it was assumed a trade of electricity at a price of 0.08 USD per kW h (UC_{EL}).

$$EW_{ANNUAL} = \dot{W}_E \cdot t_{op} \tag{16}$$

$$IN_{EL} = UC_{EL} \cdot EW_{ANNUAL} \tag{17}$$

Having the amount of ice annually produced, estimated from Eq. (6), the expected revenue from selling ice can be calculated using Eq. (18). According to the Mexican market, it is expected an income of 0.15 USD per kilogram of ice (UC_{ICE}). In the economic model, it must be also considered the annual expenditure for purchasing potable water to produce the ice, such expenditure can be calculated by means of Eq (19).

$$IN_{ICE} = UC_{ICE} M_{ICE,ANNUAL} \tag{18}$$

$$EG_{\text{H2O}} = UC_{\text{H2O}}\left(\frac{\dot{M}_{ICE} \cdot t_{op}}{\rho_{ICE}}\right) \tag{19}$$

The total annual thermal energy for direct use and the expected revenues for selling this energy can be estimated using Eqs. (20) and (21), respectively. In this study, an income of 0.0160 USD per kW h (UC_{HW}) was assumed for the direct use product. This price was assumed to make the produced energy equivalent to the thermal energy produced in a conventional boiler burning natural gas.

$$EQ_{UDU,ANNUAL} = \dot{Q}_{UDU} \cdot t_{op} \tag{20}$$

$$IN_{QUDU} = UC_{HW} \cdot EQ_{UDU,ANNUAL} \tag{21}$$

Cash flow is estimated from the projected revenues of the products obtained from the cascade system and, the expenditures for capital cost, operating and maintenance costs and water purchased for ice production, given by the Eq. (22):

$$CF = (IN_{EL} + IN_{ICE} + IN_{QUDU}) - (I_{ANNUAL} + C_{OM} + EG_{H2O}) \tag{22}$$

To complete the economic model, the net present value (NPV) that provides an estimate of the economic feasibility of the geothermal cascade system, was computed by solving Eq. (23).

$$NPV = CF\left[\frac{(1+i)^N - 1}{i \cdot (1+i)^N}\right] - I_{TOT} \tag{23}$$

2.6. Implementation

The procedure utilized to carry out the techno-economic evaluation of the geothermal cascade system and the selection of the most feasible ORC machine among all ORC candidates as well as the absorption chiller, was formulated as a simple optimization problem where two expression were separately considered as objective functions. One function is related to the system energy performance, through the overall energy efficiency given by Eq (10). This function needs to be maximized. The other objective function is related to one economic parameter, in this case the NPV given by Eq. (23). This other function needs to be maximized as well. In both cases, the decision variable was related to the nominal power output of the ORC machines listed in Table 1.

Equality constraints were introduced by the equations included in the energy model and the economic model sections, except for the overall energy efficiency and NPV, which were previously defined as objective functions. For the model implementation, it was necessary to consider a binary variable (y = 1, 0) to include only one ORC machine in the cascade system. Therefore, one equality constraint was employed to define the ORC nominal power, where “i” stands for all ORC units included in Table 1 and runs from i = 1 to i = 13:

$$\dot{W}_E = \sum_{i=1}^{13} \dot{W}_{ORC(i)} y(i) \tag{24}$$

The following constraints are related to the input temperature of geothermal hot water, evaporator temperature difference and energy efficiency of each ORC machine included in Table 1:

$$T_1 = \sum_{i=1}^{13} T_{ORC(i)} y(i) \tag{25}$$

$$\Delta T = \sum_{i=1}^{13} \Delta T_{ORC(i)} y(i) \tag{26}$$

$$\eta_{ORC} = \sum_{i=1}^{13} \eta_{ORC(i)} y(i) \tag{27}$$

In order to assure that only one ORC unit is present in the cascade system, the following constraint was included in the optimization algorithm:

$$\sum_{i=1}^{13} y(i) = 1 \tag{28}$$

Finally, two more inequality constraints for thermally activated machines were considered. The first constraint defines the minimum temperature requirement of the half-effect absorption machine and assigns a COP of 0.3. The second constraint works in a similar mode for the simple-effect absorption machine assigning a COP of 0.6. See Eqs. (29) and (30), respectively.

$$T_2 \geq 80\ ^\circ\text{C and COP} = 0.3 \tag{29}$$

$$T_2 \geq 90\ ^\circ\text{C and COP} = 0.6 \tag{30}$$

The mathematical description of the energy and economic model is classified as a Mixed Integer Non Linear Programming (MINLP), with the ORC nominal power output associated to the other parameters listed in Table 1, as well as the binary variable y(i) seen both as the decision variables. Thus, all the equations previously listed were implemented as a MINLP model in the GAMS Software environment using DICOPT as the NLP solver and BARON as the MINLP solver [27]. Once the model was implemented, it was solved in a Windows platform computer.

3. Results and discussion

The main objective of this work was the evaluation and selection of small capacity ORC and absorption units to be utilized in a cascade manner, considering conditions of geothermal fluid typical of different zones in Mexico. The proposed approach allowed determination of optimum design conditions under specification of ORC units available from different manufacturers as illustrated in Table 1. The optimization model converged to a unique solution where the two proposed objective functions were maximized separately. A discussion of the results is given below.

By solving the optimization model, appropriate ORC and absorption chiller units were selected reaching a maximum value of overall energy efficiency and economic profit. Table 2 shows the energy and economic results for the optimized cascade system. The first and second column in Table 2, present the results for the optimal configuration having the NPV and the overall energy efficiency as the objective function, respectively. It can be seen that both objective functions reach the same maximum values with around $10.738 million for the NPV and 46.3 percent for the overall energy efficiency (see values in bold in Table 2). Optimal values corresponds to the power machine coded as ORC10 (binary variable y(10) = 1), with a nominal power output of 125 kWe coupled to a single-effect absorption machine, being able to operate with geothermal hot water at a temperature of around 110 °C. Simple Return Period (SRP) was also calculated, obtaining a value of 1.7 years for both configurations. It should be considered that as the objective functions are not in conflict and both reached the same optimal figures, attempt to implement a multi-objective optimization was not performed.

As the half-effect absorption machine did not appeared as good candidate in the optimal geothermal cascade system, calculations were performed assuming that only this cooling machine was available. This calculation was done to investigate any other suitable arrangement, removing the inequality constraint given by Eq. (30) from the optimization model. The third and fourth col-

Table 2
Energy and economic results for the optimized cascade geothermal system.

Parameter	Units	$T_2 \geqslant 90$ °C (COP = 0.6)		$T_2 \geqslant 80$ °C (COP = 0.3)	
		max NPV y(10) = 1	max ETA y(10) = 1	max NPV y(10) = 1	max ETA y(2) = 1
NPV	[MUSD]	**10.738**	10.738	**5.202**	1.3326
η_{GEO}	[%]	46.3	**46.3**	36.4	**39.1**
$\dot{W}_E$	[kWe]	125.0	125.0	125.0	25.0
ΔT_{ORC}	[°C]	10.5	10.5	10.5	7.0
η_{ORC}	[–]	10.6	10.6	10.6	7.8
T_1	[°C]	109.40	109.40	109.40	95.00
T_2	[°C]	98.90	98.90	98.90	88.00
T_3	[°C]	88.90	88.90	88.90	78.00
T_4	[°C]	78.90	78.90	78.90	68.00
$\dot{Q}_{ORC}$	[kW]	1179.24	1179.24	1179.24	320.51
$\dot{M}_{GEO}$	[kg/s]	26.868	26.868	26.868	10.954
$\dot{Q}_{COOL}$	[kW]	673.85	673.85	336.92	137.36
$\dot{M}_{ICE}$	[kg/h]	31.084	31.084	15.542	6.336
$\dot{Q}_{UDU}$	[kW]	786.16	786.16	786.16	320.51
$\dot{Q}_{GEO}$	[kW]	3425.42	3425.42	3425.42	1236.26
EW_{ANNUAL}	[MW h]	930.70	930.70	930.70	186.10
$EQ_{UDU,ANNUAL}$	[MW h]	5853.80	5853.80	5,853.80	2386.50
I_{TOT}	[MUSD]	2.2517	2.2517	1.8506	1.2938
I_{ANNUAL}	[MUSD]	0.2644	0.2644	0.2173	0.1519
IN_{EL}	[USD]	74,460.00	74,460.00	74,460.00	14,892.00
IN_{ICE}	[MUSD]	0.1446	0.1446	0.7232	0.29488
IN_{QUDU}	[USD]	93,660.37	93,660.37	93,660.37	38,184.61
EG_{H2O}	[USD]	31,447.58	31,447.58	15,723.79	6410.46
C_{OM}	[USD]	26,448.52	26,448.52	21,737.57	15,197.10
CF	[MUSD]	1.2923	1.2923	0.6365	0.17438
SRP	Years	1.742	1.742	2.907	7.420

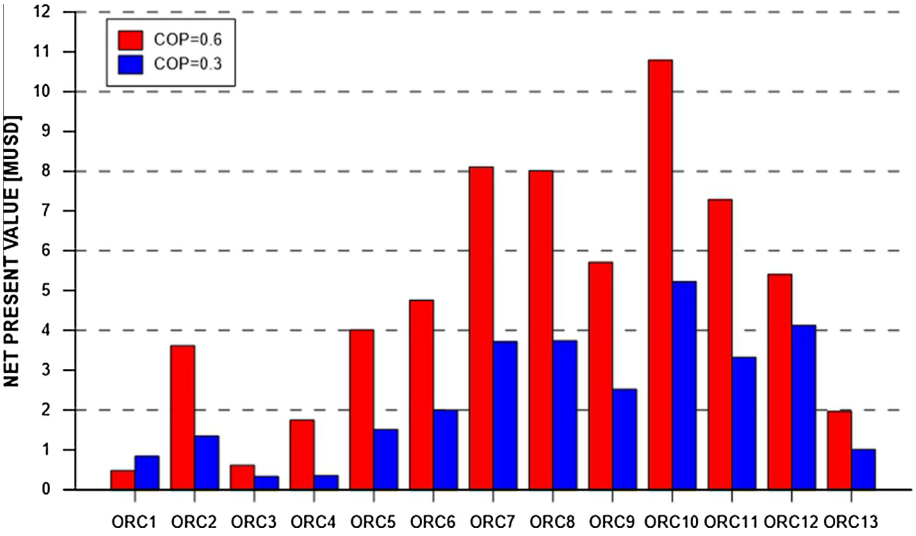

Fig. 2. NPV of cascade system for the different ORCs.

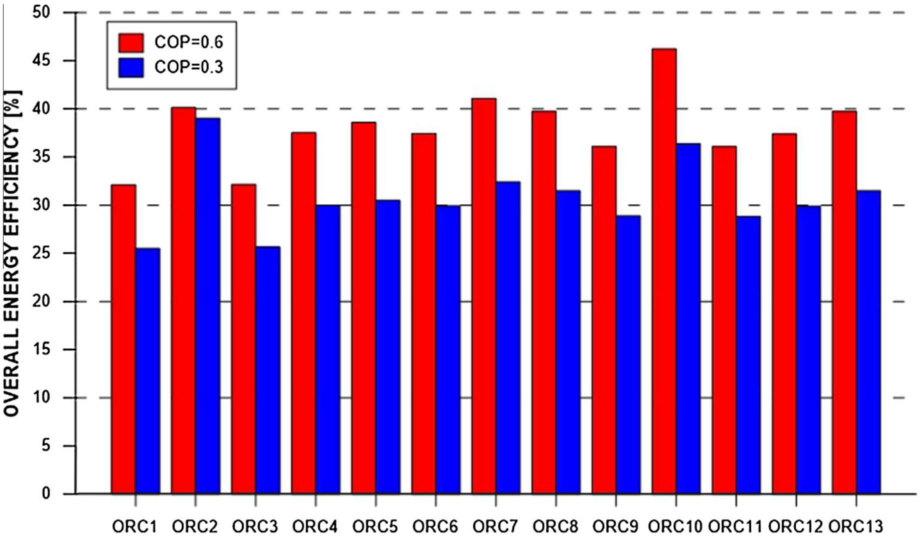

Fig. 3. Overall energy efficiency of cascade system for the different ORCs.

umns of Table 2 contain results for the case where only a half-effect absorption machine was included. The third column corresponds to maximum NPV value and the fourth column corresponds to the maximum overall energy efficiency value, respectively. It can be seen from the third column, that a value of around $5.202 million was reached, maximizing the NPV. Maximum NPV corresponds for a second time to the ORC10, a half-effect absorption machine and useful heat for further use. A simple payback of 2.9 years and overall energy efficiency of 36.4 percent were achieved for this case. The fourth column shows the results for the overall energy efficiency as objective function, achieving a maximum value of 39.1 percent. The NPV value is $1.3326 million with a simple payback of 7.42 years. This arrangement corresponds to the binary variable y(2) = 1, that is ORC02 model PMTH-25, with 25 kWe of nominal power output, coupled also with a half-effect thermally activated machine.

One interesting aspect to note in the four cases shown in Table 2, is that ORC energy efficiency and capital cost seems not to be the only important parameters influencing the correct integration of an ORC with the other thermal levels. It can be seen, by comparing temperature values of Table 2 and ORC characteristics listed in Table 1, that temperature difference in the ORC evaporator also plays an important role. The two ORC selected as optimal, correspond to units with the lowest temperature difference between evaporator inlet and outlet, 10.5 °C for ORC10 and 7.0 °C for ORC02. This means that more thermal energy is available for the next thermal level of the geothermal cascade and more profitability can be expected. However, in order to obtain any possible relationship among all the parameters listed in Table 1, as well as to determine the general behavior, the optimization model was solved excluding the previous optimized solutions in each subsequent run until a worst case was reached. Following this procedure, Figs. 2–4 were obtained.

Fig. 2 shows NPV performance for all ORC listed in Table 1. The red bars correspond to cascade geothermal systems using single-effect absorption machines and the blue bars correspond to half-effect absorption chillers. It can be seen that all configurations have a positive value of NPV, indicating economic feasibility of each configuration. Evidently, the ORC10 with a single effect absorption unit is the most competitive configuration. These

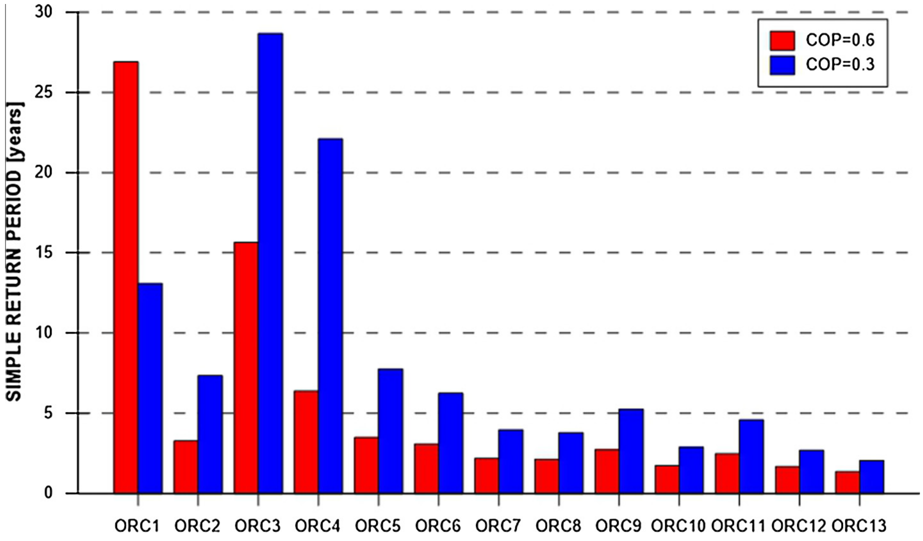

Fig. 4. Simple return period of cascade system for the different ORCs.

results highlight the fact that the cascade utilization concept overcomes the downside of low efficiency and high capital cost of ORC. On the other hand, it can be observed that NPV decreases as the temperature drop in the evaporator increases, i.e. higher NPV values are for units with lower temperature drop in the evaporator. This result confirms that most appropiate units are the ones with lowest temperature drop in the evaporator. Additionally, low ORC thermal efficiency is compensated with more thermal energy available to feed the next cascade level while producing more profit.

Overall energy performance is shown in Fig. 3, the red bars correspond to single-effect absorption machines and the blue bars correspond to half-effect units. It can be observed that systems with better overall energy efficiency are the systems including single-effect machines. However, systems including half-effect units are also attractive from an energy point of view. The configurations with the higher energy performance are the ones with higher ORC energy efficiency and lower temperature drop in the evaporator and viceversa.

Finally, Fig. 4 was prepared including SRP calculated for each configuration. In this case, the ORC13 is the system that has the lowest simple return period. However, despite this alternative seems feasible from the SRP point of view, it is more desirable to consider the NPV value in order to determine the economic feasibility of this option. In this case, no clear relationship was found among parameters listed in Table 1.

4. Conclusions

In this paper a procedure is presented for the selection of small capacity ORC and absorption machines to be integrated in a polygeneration plant using geothermal energy in a cascade manner. A simple cascade system consisting of three thermal levels operating sequentially and producing simultaneously, power, ice and useful heat was proposed and assessed. A techno-economic analysis was carried out to evaluate system performance with different ORC machines from both energy and economic point of view. The problem of selecting the most appropriate ORC, among different options available in the market, was reduced through a simple optimization algorithm including binary variables, as well as NPV and overall energy efficiency as objective functions.

It was demonstrated that ORC is a promising technology, despite the low efficiency of this type of machines. This apparent drawback was overcome by using thermal energy at different levels, increasing the overall energy efficiency of the entire process. The cascade concept also boosted the system profitability due to additional products obtained in subsequent levels. The multiproduct scheme enhances the rational use of geothermal energy and improves the economic performance of these novel schemes, which are usually penalized by high investment costs.

Particularly, it was found that ORC energy efficiency and capital cost are not the only important parameters influencing economic and energy performance of geothermal cascade systems, with the temperature difference in the ORC evaporator an important factor. It can be concluded that most appropiate ORC units are the ones with lowest temperature drop in the evaporator, achieving higher NPV values. Furthermore, low ORC thermal efficiency is not a downside because it is compensated with more thermal energy available to feed the next level making more profit. Regarding, rational energy use, configurations with the higher energy performance are the ones with higher ORC energy efficiency and lower temperature drop in the evaporator.

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