Energy and exergy analysis and comparison of different configurations of geothermal-fuelled poly-generation systems

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ABSTRACT

This paper presents and investigates several configurations of poly-generation systems fuelled by medium and low temperature geothermal water. Poly-generation has become an option that is being explored intensively to be implemented in geothermal systems of different countries, since it offers the possibility to increase the use of geothermal energy by generating electric power, thermal energy, refrigeration or air conditioning (or other forms of usable energy) simultaneously, from a single source of primary energy. In this study, different configurations of poly-generation systems are developed and modeled, which allow to analyze and select a system of auto-generation, to replace conventional forms of energetic supply, based on technological energy proposals and exergetic analysis. These poly-generation systems consist of a subsystem based on an Organic Rankine Cycle (ORC), a cooling subsystem based on an absorption machine with Thermally Activated Technology (TAT) and heat exchangers for energy direct uses. The main objectives are to identify the best configuration to produce electricity, cold and heat with higher efficiency, as well as to determine opportunity areas to improve each of the system configurations. A detailed energy and exergy analysis is performed in the EES software environment taking into account geothermal sources at the temperature range of 80-150°C. The developed codes allow a wide energetic and exergetic analysis of different configurations of cycle-arrangements that integrate poly-generation systems. Finally, a poly-generation configuration that satisfies energetic requirements posed with the intention to improve geothermal energy use efficiency, based on energy and exergetic performance parameters is selected.

Keywords: Low-to-medium temperature resources, modeling, ORC, TAT, efficiency, EES software.

Análisis de energía y exergía y comparación de diferentes configuraciones de sistemas de poli-generación que usan recursos geotérmicos

RESUMEN

Se presentan e investigan varias configuraciones de sistemas de poli-generación que emplean agua geotérmica de temperatura baja a media. La poli-generación se ha vuelto una opción cada vez más estudiada para su implementación en sistemas geotérmicos de diferentes países, ya que ofrece la posibilidad de incrementar el uso de la geotermia generando energía eléctrica, energía térmica, refrigeración o acondicionamiento de espacios (u otras formas útiles de energía) de manera simultánea, a partir de una sola fuente de energía primaria. En este estudio se desarrollaron y modelaron diferentes configuraciones de sistemas de poli-generación que permiten analizar y escoger un sistema de autogeneración para sustituir fuentes convencionales de oferta energética, con base en propuestas tecnológicas energéticas y análisis exergéticos. Estos sistemas de poli-generación consisten de un subsistema basado en un Ciclo Rankine Orgánico (ORC), un subsistema de enfriamiento basado en una máquina de absorción con Tecnología Activada Térmicamente (TAT) e intercambiadores de calor para usos directos de energía. Los objetivos principales so identificar la mejor configuración para generar electricidad, frío y calor con alta eficiencia, así como encontrar áreas de oportunidad para mejorar cada una de las configuraciones. Se realizó un análisis energético y exergético detallado mediante el software EES tomando en cuenta fuentes geotérmicas de temperatura entre 80 y 150°C. Los códigos desarrollados posibilitan un amplio análisis energético exergético de diferentes configuraciones de arreglos de ciclo que componen los sistemas de poli-generación. Finalmente, se seleccionó una configuración de poli-generación que satisface los requerimientos energéticos establecidos, con la intención de mejorar el uso eficiente de la energía geotérmica con base en análisis energéticos y exergéticos de resultados comparables.

Palabras clave: Recursos de temperatura baja a media, modelado, ORC, TAT, eficiencia software EES.

1. INTRODUCTION

Fossil fuels are the main energy source worldwide, but they affect severely the environment and human well-being. The inevitable pollution effects as well as the fact that they are resources from non-renewable nature, also involves economic and geopolitical problems. In order to face these problems, alternative sources of energy along with new forms of production, distribution and consumption of energy are being studied. As a partial solution to those problems, and in order to improve the use of energy, poly-generation systems have been considered through cascade use of medium and low enthalpy geothermal resources. Recent research in this field has the purpose to characterize poly-generation systems exploiting geothermal energy, which currently represent an interesting alternative for generation of electricity, cold and heat at large scale, due to potential economic and ecological advantages and operating flexibility. Low-grade heat is the most appropriate heat source for Organic Rankine Cycle (ORC) systems, which in addition are the most viable devices to integrate in poly-generation systems with cascade use of medium and low enthalpy geothermal energy (Hettiarachchi et al., 2007).

This paper focuses on geothermal resources with temperature ranging from 80-150°C and integration of geothermal applications and direct uses within this temperature range. Possible configurations or cascade arrangements are compared to each other using energy and exergy tools. The purpose is to address some design challenges by developing an integral analysis of poly-generation geothermal energy systems, demonstrating the benefits of this framework through its application to cascade use of medium-low enthalpy geothermal sources. Particularly, this paper presents eight connection alternatives for integration of a poly-generation plant. Here, the focus is mainly for increasing power production and improve energy utilization efficiency by reducing heat losses. Geothermal water chemistry is not considered due to the generally low salinity of the water under that temperature range, as well as the availability of components manufactured with materials with very low corrosion potential. In order to evaluate the ORC net power output, the total exergetic efficiency and the irreversibility relative to flows id determined, as well as the main parameters of systems, including supply temperatures and heat requirements. The working fluid for the ORC is R245fa and the pair NH_3/H_2O are the working fluids for the absorption subsystem. The transport and thermodynamic properties of R245fa and NH_3/H_2O pair are calculated using the EES software.

2. LITERATURE REVIEW

This section presents a short review of exergy analysis applied to some geothermal plants, aimed to highlight the importance of this concept. Yari (2010) carried out a comparative study of different concepts of geothermal power plants, based on exergetic analysis. Heberle and Brüggemann (2010) considered the option of combined heat and power generation using geothermal resources with temperature below 450°K. They compared through second-law analysis, series and parallel circuits of an ORC and additional heat generation. Guo et al. (2010) presented a detailed energy and exergetic analysis of a low temperature geothermal ORC, selecting appropriate working fluids for specific heat source conditions. The fluid R245fa is recommended as the most suitable for low temperature geothermal energy conversion applications.

Li et al. (2013) analyzed the option of combined heat and power generation altogether with oil recovery using geothermal water ranging from 100 to 150°C. They presented and compared through thermodynamic analysis of the first and second law, circuits in series and parallel of an ORC, an oil collection and heat transport subsystem, including oil recovery. Fiaschi et al. (2014) proposed and analyzed a CHP (Combined Heat and Power) configuration called cross-parallel CHP in order to identify potential reduction of irreversibilities in heat exchangers and losses to environment related to re-injection of geo-fluids. Akbari et al. (2014) proposed and analyzed a combined cogeneration system to produce electricity and pure water. The system used geothermal energy as a heat source and consisted of a Kalina cycle, a LiBr/H_2O absorption system and a water purification system. Luo et al. (2016) studied an integrated cascade system of geothermal discharge waters from a flash geothermal power plant. The discharged geothermal water from the power plant was proposed for cascade use in two stages of LiBr/H_2O absorption cooling, drying of agricultural products, and residential baths. As for ORC-CHP systems fuelled by geothermal water, it can be seen that little research has been carried out. Considering poly-generation with cascade arrangements, there is much to be done, being very important to perform different analysis intended to determine the best possible forms of exploiting geothermal energy.

3. DESCRIPTION OF SYSTEMS

This section describes the basic conceptual poly-generation arrangements intended to use low-grade geothermal resources. Three main technologies are considered: Organic Rankine Cycle (ORC), Thermally Activated Technology (TAT) and heat exchangers (HX), producing simultaneously power, cooling and useful heat for direct uses. Eight configurations are proposed in order to determine the best energy and exergetic option for a better exploitation of medium and low temperature geothermal sources: Series system 1 (SC1), Parallel system (PC), Hybrid series-Parallel system 1 (HPS1), Hybrid Parallel-series system 2 (HPS2), Hybrid Parallel-Series system 3 (HPS3), Series system 2 (SC2) and Series system 3 (SC3). Figure 1, a) through h), shows the symbolic schemes for these eight configurations. A description of each arrangement is given next.

Series system (SC1). This arrangement is considered as the most common way to exploit geothermal energy in cascade. The configuration consists of three thermal levels with one component per level that operates sequentially and simultaneously. According to Figure 1a, ORC subsystem is placed on first level, refrigeration machine (TAT) on second level and a heat exchanger (HX) for direct use in last level. In this configuration, ORC converts initially contained energy into geothermal resource to generate electricity, and then the geothermal fluid flows from ORC to cooling subsystem and then to heat exchanger subsystem for direct use. The capacity of TAT subsystems and HX depend on the geothermal fluid temperature at the ORC outlet and the cooling subsystems, respectively. The available geothermal fluid passes completely through each of subsystems.

Parallel system (PC). In this configuration the geothermal resource flow is divided equally for three subsystems. It is recommendable when the geothermal fluid temperature is not so high but it is sufficient for activate each component (ORC, TAT and HX). The volume of the geothermal flow can also be divided according to the desired amount of power, cooling and heat. The entire system is formed with a single temperature level and the components can be integrated in parallel with the simultaneous production, but not sequentially (Figure 1b).

Hybrid Series-parallel system (HSP). In this case, the HSP can be considered a modified version of series system, SC1. In this arrangement, the entire geothermal flow is used for power production at the cascade first level. Then, the flow at the ORC output is split equally for the remaining two subsystems to form a second level in which TAT and HX devices works in parallel (Figure 1c). HSP system is appropriate when power production has priority, and the other products are complementary.

Hybrid Parallel-serial system 1 (HPS1). In contrast to the HSP configuration, this arrangement is considered a modified version of parallel system (PC) where most of geothermal energy is used for cooling and as useful heat for direct use at the first level of cascade. Subsequently, the outflow of TAT and HX subsystems are combined to feed an ORC subsystem for power production and thus form a cascade second level (Figure 1d). In this configuration, the size or capacity of TAT and HX subsystems are defined first, and the ORC subsystem capacity results from outlet conditions of the first level subsystems. This configuration is appropriate when cooling and heating are primary requirements and power production is complementary. This type of arrangement is possible since there are currently on market ORC machines that can operate at temperatures as low as 80°C.

Hybrid Parallel-series system 2 (HPS2). This configuration is a modification of the HPS1 system, where most of geothermal energy is used to generate electricity and cold in the cascade first level. Subsequently, the outflow of ORC and TAT subsystems are combined to feed a HX subsystem for production of heat for direct uses and thus form the cascade second level (Figure 1e). In this configuration the size or capacity of ORC and TAT subsystems are defined first and HX subsystem capacity results from the outlet conditions from the first level. This configuration is appropriate when electricity and cold generation are primary needs and production of heat is complementary.

Hybrid Parallel-series system 3 (HPS3). This configuration is a modification of the HPS1 system, where most of geothermal energy is used to generate electricity and heat at cascade first level. Subsequently, the outflow of ORC and HX subsystems are combined to feed a TAT subsystem for cold production and thus form a cascade second level (Figure 1f). In this configuration the size or capacity of ORC and HX subsystems are defined first, and therefore the capacity of the TAT subsystem results from the outlet conditions from first level. This configuration is appropriate when power and heat are the primary needs and production of cold is complementary.

Series system 2 (SC2). This arrangement is a modification of the SC1 configuration. The configuration consists of three thermal levels with one component per level that operates sequentially and simultaneously. According to Figure 1g, geothermal flow is split equally in two streams, one to feed the ORC subsystem on first level, and the second is combined with the ORC outlet flow to feed a cooling machine (TAT) at second level. Then the flow is sent to a Heat Exchanger (HX) for direct use on the last level. In this configuration, ORC transforms geothermal energy into electricity, and then the geothermal fluid from ORC is combined with the second stream to pass through the cooling subsystem. Afterwards, all the flow goes to a heat exchanger subsystem for direct use.The capacity of TAT and HX subsystems depend on the geothermal fluid temperature from the streams at the ORC outlet and the second stream, and on the cooling subsystem outlet stream, respectively.

Series system 3 (SC3). This arrangement is also a SC1 configuration modified. The configuration consists of three thermal levels with one component per level that operates sequentially and simultaneously. According to Figure 1h, the geothermal flow is split equally in two streams, one feeding the ORC subsystem at first level and, the remaining combined with TAT subsystem outlet flow to feed direct-use heat exchanger (HX) at the third level. In this configuration, ORC converts initially the energy contained in the geothermal resource to generate electricity; when the geothermal fluid flows out of the ORC, it is passed to a TAT subsystem to generate cold. The TAT subsystem outlet flow is combined with a second stream to pass to the heat exchanger subsystem for direct use. The capacity of the TAT subsystem depends on the ORC subsystem outlet temperature, and the subsystem HX depend on resulting temperature from combination of streams at the TAT outlet.

4. ENERGY AND EXERGY ANALYSIS

The previous section described the configurations, operation and equipments used in subsystems that integrate eight different configurations. In this section there is enough information to determine the thermodynamic states at each specific point of the systems. It is important to establish the considerations and assumptions to determine all thermodynamic states and mass flows.

In this study, computer programs have been developed to investigate the first and second law behavior of poly-generation systems. The computer program is developed in engineering equation solver (EES) software. The developed computer programs are based on heat and mass balances, heat transfer equations and the state equations. EES software provides high accuracy thermodynamic properties for water and R245fa. The thermodynamic properties of NH_3/H_2O solution are calculated by using property database or developed procedure NH_3/H_2O. The known conditions read into the programs include typical data from geothermal reservoirs and using given parameters. The program calculates at all points the temperature, enthalpy, entropy, mass flow rate, concentration and exergy of the working fluids.

4.1 Considerations and assumptions

- The proposed geothermal poly-generation systems operate at steady-state condition.
- Isentropic efficiencies for turbines and pumps are 80 and 70%, respectively.
- The geothermal fluid is saturated liquid at the stream 1.
- The properties for geo-fluids are considered those of the pure water.
- Temperature and pressure losses in separation and condensation processes are neglected.
- Cooling water temperature is 25°C.
- The geothermal flow considered is 20 kg/s with temperatures ranging from 80 to 150ºC.
- In refrigeration systems, the refrigerant can reach saturation states both at outlet of condenser and at outlet of evaporator.
- Mixtures are in equilibrium both at the output of generator and at output of absorber at operating temperature corresponding to each device.
- Effectiveness of heat exchangers and solution pump are 0.7 and 0.6, respectively.
- Design temperature in the evaporator is 0°C for refrigeration.
- Design temperature in condenser and absorber is 30°C.
- Temperature of generator depends on configuration and corresponding temperature.
- All heat rejection components (ORC and cooling machine) reject heat to cooling water system.

4.2 Energy balance and exergy destruction

Mass, energy and exergy balances for any control volume at steady state can be expressed by equations 1, 2, and 3, respectively:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$0 = \dot{Q} - \dot{W} + \sum \dot{m}_{in}\left(h_{in} + \frac{1}{2}V_{in}^2 + gz_{in}\right) - \sum \dot{m}_{out}\left(h_{out} + \frac{1}{2}V_{out}^2 + gz_{out}\right) \quad (2)$$

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W} + \sum \dot{m}_{in}\, b_{in} - \sum \dot{m}_{out}\, b_{out} - \dot{B}_d \quad (3)$$

Where Q and W are net heat input and work output, m is mass flow of fluid, h is enthalpy, in and out are sub-indexes for input and output, T_J is the temperature at which heat transfer takes place. The specific flow exergy and the rate of total exergy are given by:

$$b = (h - h_0) - T_0(s - s_0) \tag{4}$$

Where the subscript 0 stands for the restricted dead state and T_0 is the dead state temperature. The energy and exergy efficiencies are generally defined as:

$$\eta_t = \left(\frac{\dot{W}_{Net} + \dot{Q}_{Cooling} + \dot{Q}_{DU}}{\dot{Q}_{Geo}}\right) \tag{5}$$

$$\dot{Q}_{Geo} = \dot{m}_1 Cp_{w1}(T_1 - T_4) \tag{6}$$

$$\eta_{ex} = \left(\frac{\dot{W}_{Net} + \dot{B}_{Cooling} + \dot{B}_{DU}}{\dot{B}_{in}}\right) \tag{7}$$

$$\dot{B}_{in} = \dot{B}_1 - \dot{B}_4 \tag{8}$$

Energy and exergy balances are provided in Table 1 for the components, where flow streams are based on states identified in Figure 2. Exergetic analysis, accounting for irreversibilities of poly-generation systems, also allows to analyze the performance of systems in exergetic terms in order to understand more accurately the true performance of an ORC subsystem, the true coefficient of performance of cooling subsystem and the true global efficiency.

Table 1. Energetic and exergetic relations for the subsystems of poly-generation configurations.

Equipment	Energy relations	Exergy relations
Evaporator (ORC)	$\dot{Q}_{ORC} = \dot{m}_8(h_5 - h_8)$ $\dot{Q}_{ORC} = \dot{m}_1(h_1 - h_2)$	$\dot{B}_{D,Eva} = (\dot{B}_1 + \dot{B}_8) - (\dot{B}_2 + \dot{B}_5)$
Turbine (ORC)	$\eta_T = \frac{(h_5 - h_6)}{(h_5 - h_{6S})}$ $\dot{W}_T = \dot{m}_5(h_5 - h_6)$	$\dot{B}_{D,T} = (\dot{B}_5 - \dot{B}_6) - \dot{W}_T$
Electric generator (ORC)	$\dot{W}_e = \dot{W}_T * \eta_G$	$\dot{B}_{D,G} = \dot{W}_T - \dot{W}_e$
Condenser (ORC)	$\dot{Q}_{COND} = \dot{m}_6(h_6 - h_7)$ $\dot{Q}_{COND} = \dot{m}_9(h_{10} - h_9)$	$\dot{B}_{D,Cond} = (\dot{B}_6 + \dot{B}_9) - (\dot{B}_7 + \dot{B}_{10})$
Pump (ORC)	$\eta_P = \frac{(h_{8S} - h_7)}{(h_8 - h_7)}$ $\dot{W}_P = \dot{m}_7(h_8 - h_7)$	$\dot{B}_{D,P} = (\dot{B}_7 - \dot{B}_8) + \dot{W}_P$
Generator (TAT)	$\dot{Q}_{Gen} = \dot{m}_{14}h_{14} + \dot{m}_{17}h_{17} - \dot{m}_{13}h_{13} - \dot{m}_{18}h_{18}$ $\dot{Q}_{Gen} = \dot{m}_2(h_2 - h_3)$	$\dot{B}_{D,Gen} = (\dot{B}_2 + \dot{B}_{13} + \dot{B}_{18})$ $-(\dot{B}_3 + \dot{B}_{14} + \dot{B}_{17})$
Rectifier (TAT)	$\dot{Q}_{Rec} = \dot{m}_{17}h_{17} - \dot{m}_{18}h_{18} - \dot{m}_{19}h_{19}$ $\dot{Q}_{Rec} = \dot{m}_{23}(h_{24} - h_{23})$	$\dot{B}_{D,Rec} = (\dot{B}_{17} + \dot{B}_{23})$ $-(\dot{B}_{18} + \dot{B}_{19} + \dot{B}_{24})$
Condenser (TAT)	$\dot{Q}_{CONDEN} = \dot{m}_{19}(h_{19} - h_{20})$ $\dot{Q}_{CONDEN} = \dot{m}_{25}(h_{26} - h_{25})$	$\dot{B}_{D,Conden} = (\dot{B}_{19} + \dot{B}_{25})$ $-(\dot{B}_{20} + \dot{B}_{26})$

Evaporator (TAT)	$\dot{Q}_{EVAP} = \dot{m}_{21}(h_{22} - h_{21})$ $\dot{Q}_{EVAP} = \dot{m}_{27}(h_{27} - h_{28})$	$\dot{B}_{D,Evap} = (\dot{B}_{21} + \dot{B}_{27}) - (\dot{B}_{22} + \dot{B}_{28})$
Absorber (TAT)	$\dot{Q}_{ABS} = \dot{m}_{16}h_{16} + \dot{m}_{22}h_{22} - \dot{m}_{11}h_{11}$ $\dot{Q}_{ABS} = \dot{m}_{29}(h_{30} - h_{29})$	$\dot{B}_{D,Abs} = (\dot{B}_{22} + \dot{B}_{16} + \dot{B}_{29}) - (\dot{B}_{11} + \dot{B}_{30})$
SHX (TAT)	$\epsilon_{SHX} = \frac{(T_{13} - T_{12})}{(T_{14} - h_{12})}$	$\dot{B}_{D,SHX} = (\dot{B}_{12} + \dot{B}_{14}) - (\dot{B}_{13} + \dot{B}_{15})$
Pump (TAT)	$\eta_P = \frac{(h_{12S} - h_{11})}{(h_{12} - h_{11})}$ $\dot{W}_{P,TAT} = \dot{m}_{11}(h_{12} - h_{11})$	$\dot{B}_{D,P,TAT} = (\dot{B}_{11} - \dot{B}_{12}) + \dot{W}_{P,TAT}$
Valve1 (TAT)	$h_{15} = h_{16}$	$\dot{B}_{D,Valv1} = (\dot{B}_{15} - \dot{B}_{16})$
Valve2 (TAT)	$h_{20} = h_{21}$	$\dot{B}_{D,Valv2} = (\dot{B}_{20} - \dot{B}_{21})$

5. RESULTS AND DISCUSSION

The above analysis has allowed to compare energetically and exergetically the eight poly-generation systems proposed. From this analysis it is possible to determine the advantages of using geothermal energy at its maximum potential. Following is an evaluation of the exergetic performance of the different systems proposed. First, it is analyzed how energy utilization devices in poly-generation systems take part, then the system energy and exergetic parameters are obtained, and finally it is assessed the sensitivity of the system to the variation of the operating temperatures of the poly-generation systems.

Table 2 shows a summary of the most important parameters in energy and exergetic analysis of the proposed poly-generation systems. These results compare the systems performance at 130°C and pre-specified conditions as a typical case, due to we consider this temperature could be the most probably to be found. On one hand, at these conditions the first configuration SC1 offers an exergy efficiency of 56.32% as the highest of the analyzed configurations, while HPS3 system presents the lowest with 46.17%. Comparing the results, it can be observed that the SC1 configuration gives a substantial advantage of 4.06% on exergetic efficiency over the system with the second best efficiency (Fig. 3). In addition, SC1 also offers the best benefits with respect to the different products obtained together with 283.1 kW_e of net power, 135.1 refrigeration tons and 1677 kW_{th} of heat.

Table 2. Relevant parameters of energy and exergetic analysis at 130°C.

Parameter / System	SC1	PC	HSP	HPS1	HPS2	HPS3	SC2	SC3
Geothermal resource temp. (ºC)	130	130	130	130	130	130	130	130
Reinjection temperature (ºC)	70	110	85	85	90.08	95	85.05	90.08
Geothermal heat (kW_{th})	5060	1698	3805	3804	3384	2964	3801	3379
W_NET (kW_e)	283.1	102.2	286.6	249.3	144	141.7	141.6	141.7
Thermal efficiency ORC (%)	11.41	11.41	11.41	9.91	11.41	11.41	11.41	11.41
Exergetic efficiency ORC (%)	46.6	46.6	46.6	46.22	46.6	46.6	46.6	46.6
COP	0.5596	0.5647	0.5596	0.5647	0.5647	0.5445	0.5604	0.5596
Q Refrigeration (RT)	135.1	31.54	67.56	48.15	48.08	131.6	120.7	68.16

Q Direct use (kW_{th})	1677	566.4	840	549.8	1181	594.8	1179	1181
Global thermal efficiency (%)	38.19	35.53	29.25	27.85	44.14	40.35	45.91	46.23
Global exergetic efficiency (%)	56.32	47.71	48.13	47.82	51.76	46.17	46.48	52.26

Regarding irreversibilities that allow to identify the devices in which the greatest energy losses occur, the Table 3 shows the exergetic analysis results of the equipment subsystems in every configuration. There we can appreciate that SC1 is the system that most total exergy destroys with 499 kW, followed by SC2 system with 408.28 kW. In regards to the equipment subsystems, in the case of the SC1 configuration the ORC (evaporator, turbine, generator, condenser and pump) contributes with most (52%) of the total exergy destruction. Thus, the system is important to seek alternatives for improvements in reduction exergy destruction. For the case of individual components, the Table 3 shows also that the ORC's evaporator and condenser besides TAT evaporator and HX are the devices with greater exergy destruction (see also Fig. 4).

Table 3. Exergy destruction by equipment of poly-generation configurations at 130°C.

Equipment	SC 1 (kW)	PC (kW)	HSP (kW)	HPS1 (kW)	HPS2 (kW)	HPS3 (kW)	SC 2 (kW)	SC 3 (kW)
Evaporator (ORC)	122.4	40.81	122.4	94.07	61.21	61.21	61.21	61.21
Turbine (ORC)	70.28	23.43	70.28	60.67	35.14	35.14	35.14	35.14
Electric generator (ORC)	6.256	2.085	6.256	5.35	3.128	3.128	3.128	3.128
Condenser (ORC)	54.68	18.23	54.68	53.35	27.34	27.34	27.34	27.34
Pump (ORC)	4.68	1.56	4.68	3.273	2.34	2.34	2.34	2.34
Generator (TAT)	7.798	10.16	3.899	15.19	14.06	6.147	19.29	3.644
Rectifier (TAT)	18.05	20.83	9.026	31.15	31.89	23.29	34.95	9.351
Condenser (TAT)	2.0075	0.4944	1.037	0.7393	0.6455	1.769	1.854	0.9159
Evaporator (TAT)	82.77	19.72	41.38	29.5	28.43	77.9	73.96	40.34
Absorber (TAT)	17.55	8.057	8.773	12.05	12.18	16.6	25.49	8.594
SHX (TAT)	15.9	4.232	7.949	6.329	5.898	14.13	14.08	7.319
Pump (TAT)	3.391	0.3462	1.696	0.5177	0.4991	3.181	1.698	1.647
Valve 1 (TAT)	5.117	1.219	2.558	1.824	1.609	4.546	4.572	2.354
Valve 2 (TAT)	2.85	0.2296	1.425	0.3359	0.3215	2.665	1.234	1.38
HX	85.34	49.57	51.42	74.36	119.2	74.36	102	119.2
Total	499.07	200.97	387.46	388.71	343.89	353.75	408.29	323.90

Figure 5 shows the behavior of the SC1 system in a temperature range from 80 to 150°C. According to this figure, not necessarily a higher geothermal resource temperature represents a better system's performance. For instance, the highest efficiency in this system occurs at 100°C. This implies that in most cases it is not fully exploited all the possible applications and uses of the resource.

6. CONCLUSIONS

This paper presents energy and exergetic analyses results for a set of eight configurations of poly-generation systems. The main conclusions of those analyses are as follows:

• The SC1 system is the configuration with better energy and exergetic performance and energy advantages in the products it provides, followed by the SC3 system. In the case of SC1 system, this is because energy is used in a higher range of utilization. In the case of the SC3 system, it is due to its similarity to the SC3 system.

• It is recommendable consider the option of using configurations where ORC and TAT subsystems are located at first level in geothermal resource use.

• Opportunity areas for improvement are located in the ORC subsystem due to it is the subsystem that more exergy destroys.

• Opportunity areas for improvement in the equipment are in the ORC evaporator, the ORC turbine, the TAT evaporator and heat exchanger (HX) for direct uses. This is because heat-exchange devices destroy a large portion of energy in heat transfer process, and because the power devices for these applications have low efficiencies.

• R245fa fluid has a high potential with a high relative thermal efficiency, desirable properties for plants and is environmentally safe. This fluid yields one of the best exergetic efficiencies, and a good effectiveness in the heat exchanger.

• According to exergetic analysis, the exergy destruction at high temperatures of the ORC heat exchanger represents the largest proportion of total exergy destruction.

Finally we can conclude that the combination of technologies in the different configurations proposed here to produce power, cold and heat are good alternatives for using medium and low enthalpy geothermal resources. These combinations offer a wide range of applications adaptable to specific projects and particular needs, with good performances and advantages.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the Mexican Ministry of Energy (SENER) for the funds granted to project P16 of the Mexican Center for Innovation in Geothermal Energy (CeMIE-Geo). The National Council for Science and Technology (CONACYT) as well as the UMSNH are also acknowledged for their support and financial funds.

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FIGURES IN FOLLOWING PAGES

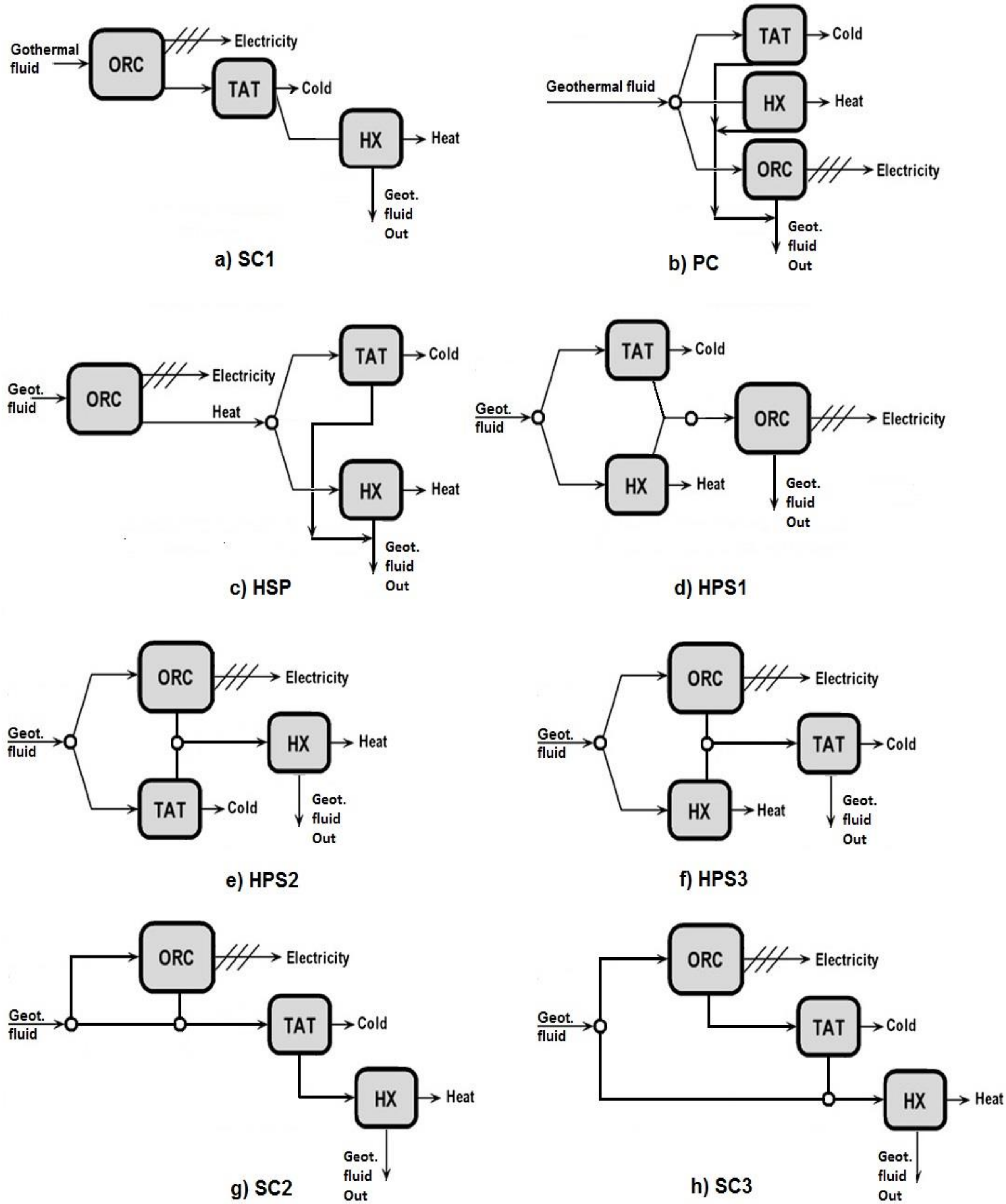

Figure 1. Symbolic schemes of the eight configurations of poly-generation systems studied.

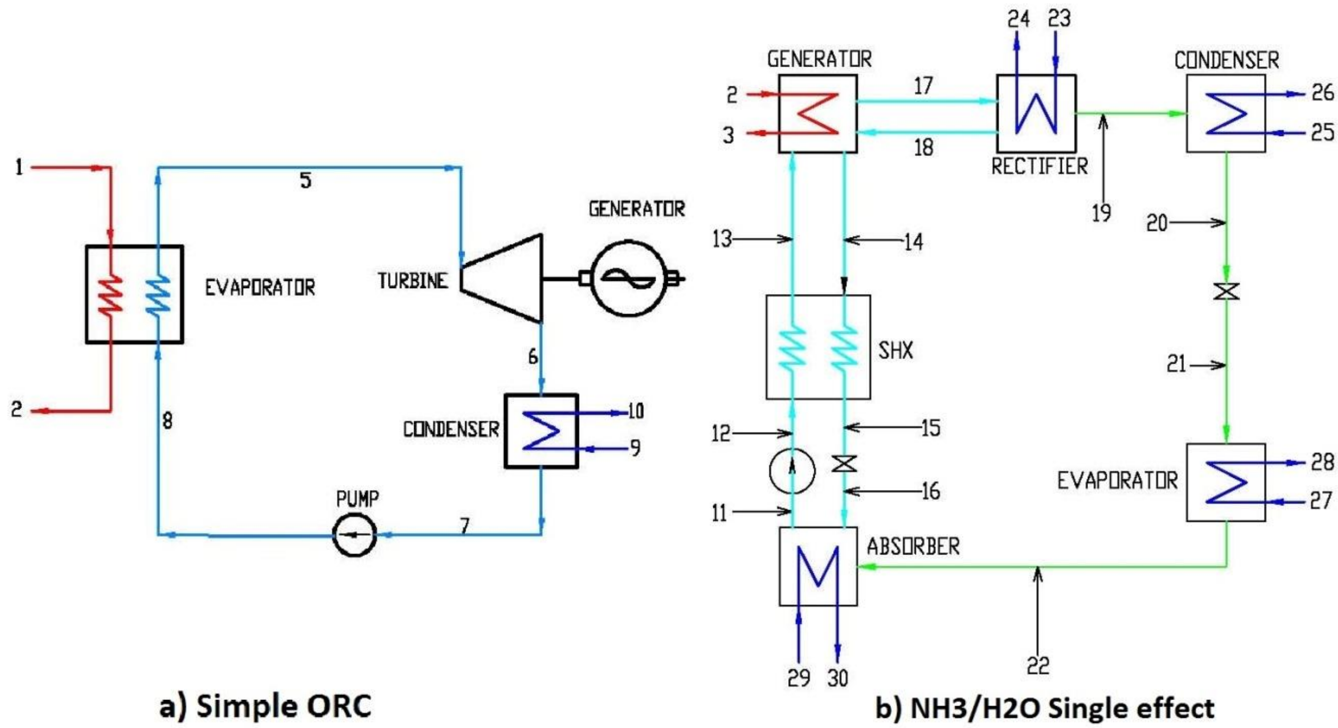

Figure 2. Schematic diagrams: (a) ORC subsystem and (b) TAT subsystem.

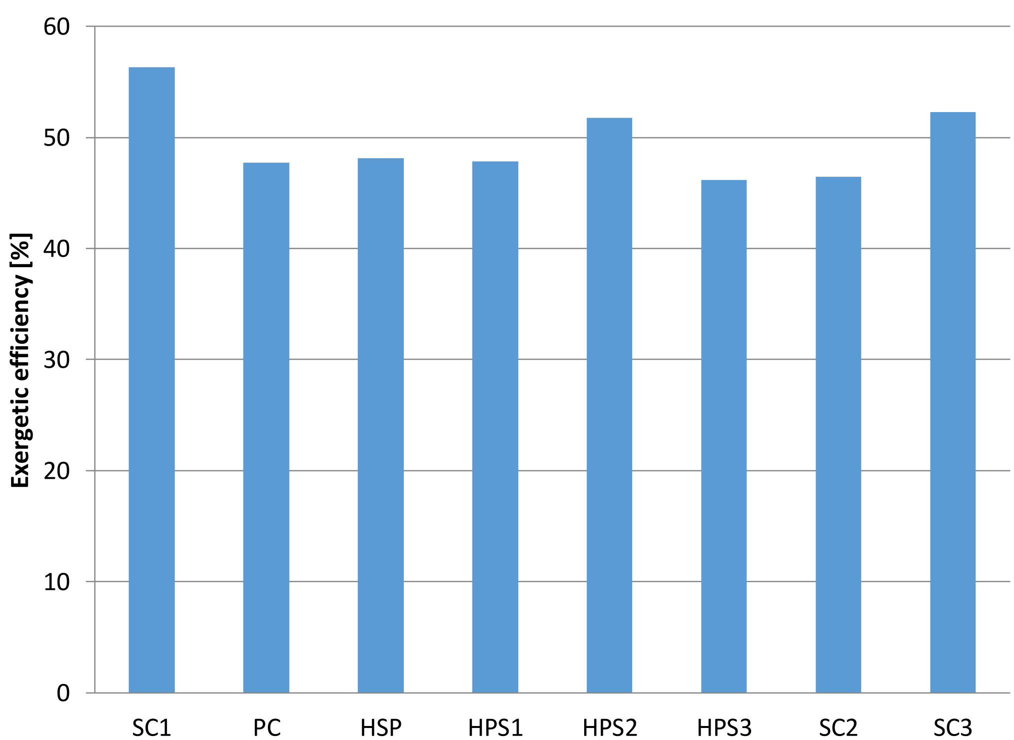

Figure 3. Comparison of exergetic efficiency of the eight poly-generation configurations at 130°C.

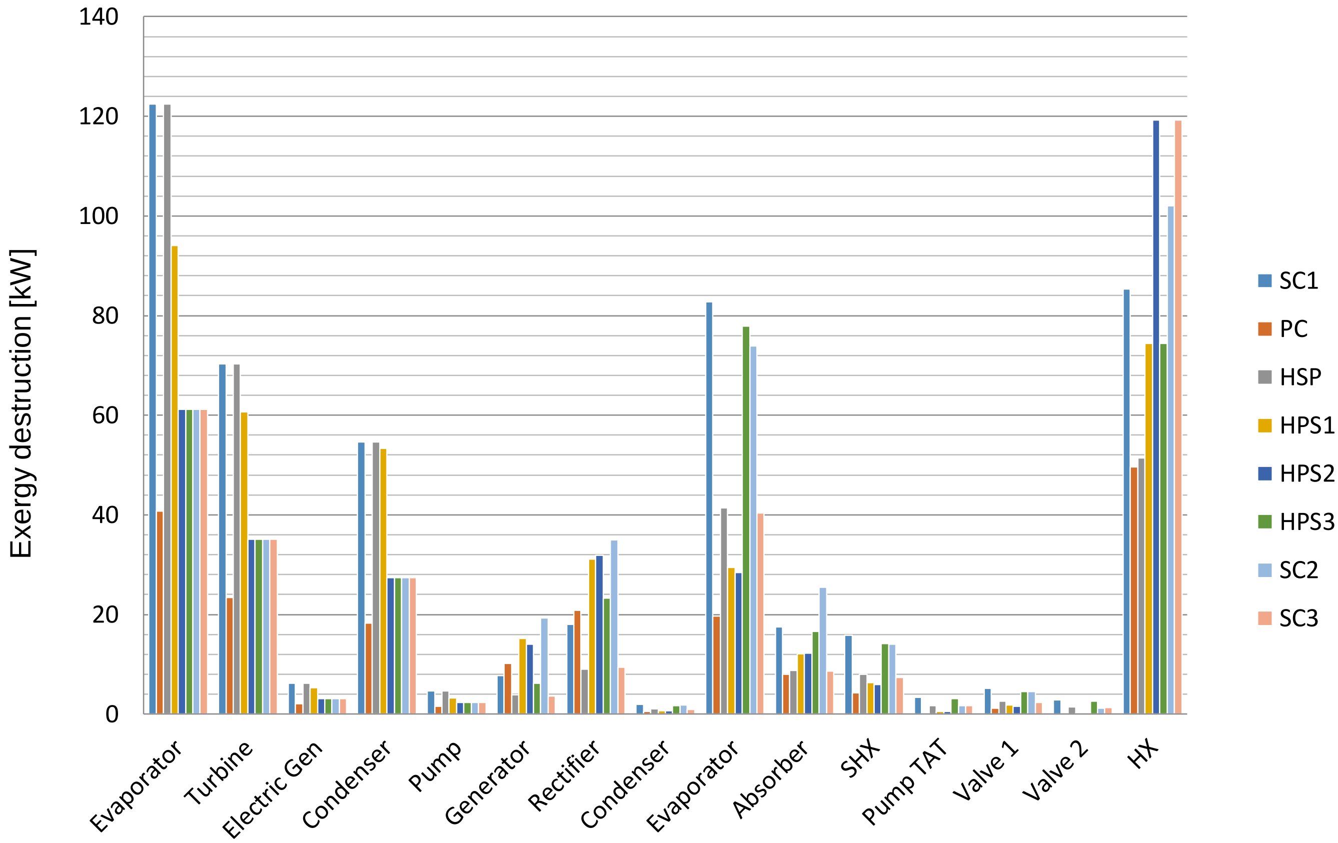

Figure 6. Exergy destruction by equipment of each of proposed systems at 130 °C.

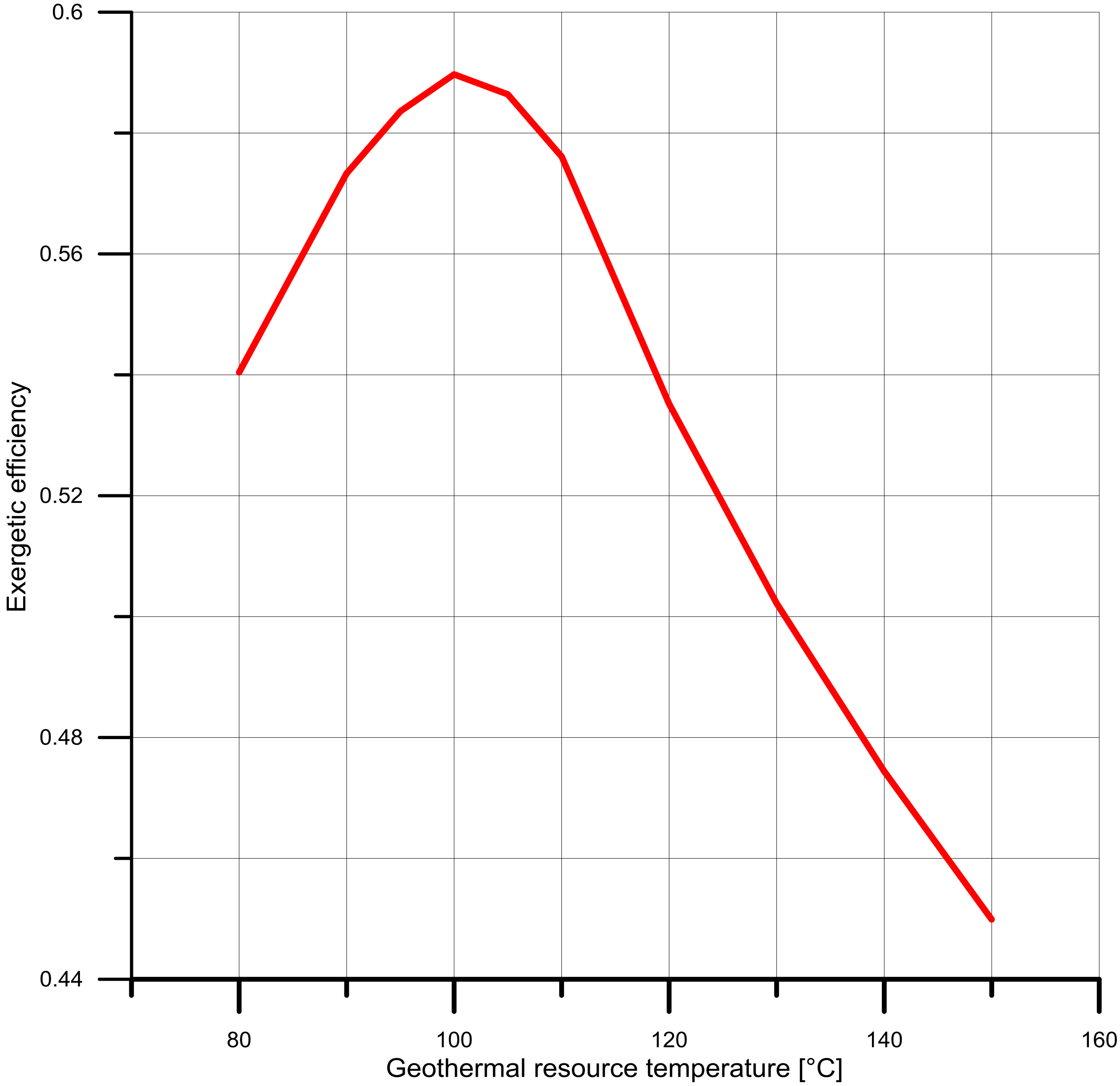

Figure 5. Exergetic performance of the SC1 system with resource temperature variation.