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A critical review of power generation using geothermal-driven organic Rankine cycle

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ABSTRACT

Organic Rankine Cycle (ORC) is a promising electricity production technology that exploits low and medium heat sources. Usually, renewable and alternative heat sources can be used in order to feed an ORC with heat. The exploitation of geothermal energy is a usual and sustainable way to feed an ORC because it is a sustainable, abundant, economical and environmentally friendly choice. The main objective of this study is to review and to discuss the geothermal-driven ORC systems for power generation in a detailed way. Moreover, the special novelty is the emphasis that is given in the use of geothermal ORC systems inside cogeneration, trigeneration and polygeneration units. Both experimental and numerical investigations are included in the present work, while they are discussed in energy, exergy and economic terms. It is found that the geothermal-driven ORC systems are viable investments with relatively low payback periods, as well as these systems lead to high energy efficiency. Moreover, it is concluded that a 20% to 30% increase in the performance of geothermal-fed ORC systems is possible by optimization. Lastly, it is useful to state that the polygeneration systems that include geothermal-driven ORCs are promising units that present high exergy efficiency values.

1. Introduction

1.1. Geothermal energy

The use of fossil fuels for producing electricity has very important drawbacks such as high levels of greenhouse gas emissions, acid rain, global warming, and depletion of the ozone layer [1]. Renewable resources can be regarded as reliable and clean energy resources for meeting the required electricity and heat duties [2]. Geothermal energy is a clean energy source that can be converted into heating of various temperature levels and so it is able to produce many useful outputs like electricity [3]. It is worth mentioning that 43,000,000 EJ geothermal energy is stored at depths up to 3000 m. The temperature of the geothermal heat resources ranges from 50 °C to 350 °C. 70% of these huge geothermal resources are water-dominated low-enthalpy resources with temperatures below 150 °C [4].

Geothermal plants are found in tectonically active locations such as Iceland, Italy, Turkey and New Zealand. The organic Rankine cycle market has experienced substantial growth since the early 2000 s. In the world, geothermal installed capacity has increased from approximately

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Abbreviations: ANFIS, Adaptive neuro-fuzzy inference system; ANNs, Artificial neural networks; AR, Absorption refrigeration; CCHP, Combined cooling, heating and power; CCP, Combined cooling and power; CHP, Combined heating and power; CSP, Concentrated solar power; DF, Double-flash; DFORC, Double-flash organic Rankine cycle; FORC, Flash-organic Rankine cycle; GPP, Geothermal power plant; GWP, Global warming potential; IGCC, Integrated gasification combined cycle; HRS, Heat recovery system; HTF, Heat transfer fluid; KC, Kalina cycle; LNG, Liquefied natural gas; MGS, Multigeneration system; MLP, Multilayer perceptron; ORC, Organic Rankine cycle; OGTHT, Oil gathering and transportation heat tracing; PSO, Particle swarm optimizer; PTORC, Parallel two-stage organic Rankine cycle; SF, Single-flash; TOPSIS, Technique for order preference by similarity to the ideal solution; TSORC, Two-stage serial organic Rankine cycle; TU, Thermal utility; VAC, Vapor absorption chiller.

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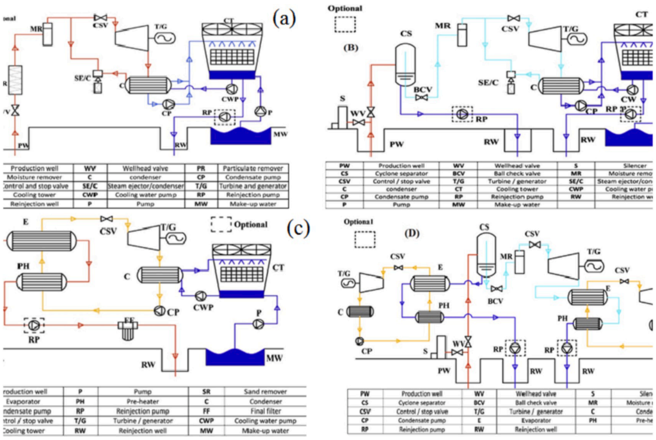


Fig. 1. Diagram of different geothermal power plants including: a) a dry steam plant b) a single-flash plant c) a basic binary geothermal power plant d) a hybrid steam-binary geothermal power plant [10]. (License Number: 5114780622087).

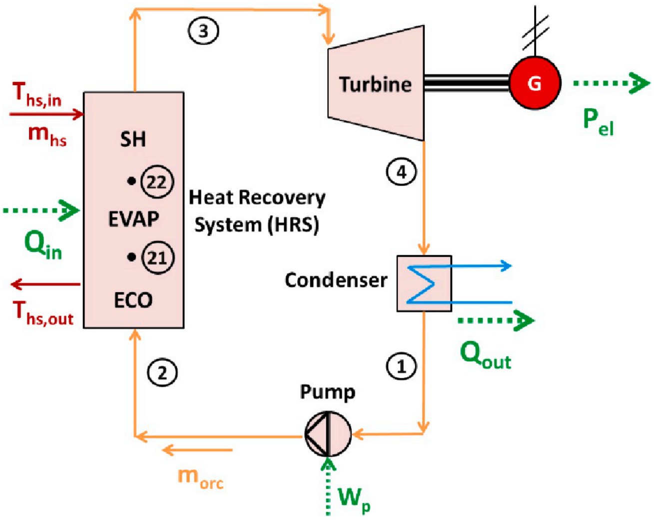


Fig. 2. The basic organic Rankine cycle.

9992 MW in 2010 to around 13,931 MW in 2019 (Haghighi et al. [5]). Hydrothermal plants provide the heat stored in natural aquifers with high values of enthalpy to generate electrical power by dry steam, single flash and double flash cycles [6,7]. Deep and improved geothermal plants are of the more recent technologies that aim at heat stored in reserves deeper than natural aquifers [8]. A hydrothermal reservoir can be formed by trapping steam in permeable and porous rocks under an impermeable layer.

In order to produce electrical power from the geothermal (or hydrothermal) resources, wells are drilled into a geothermal reservoir and geothermal fluid is brought to the surface. By employing a geothermal power plant, the heat is converted into power through turbines. There are four kinds of geothermal power plants are employed for power generation [9]:

(a) **Dry steam systems:** In dry steam systems, the temperature of the reservoir is about 370 °C, and high-pressure steam is produced. Dry steam (or supercritical) systems supply the highest amount of energy per fluid mass. In this case, steam is generated directly from the geothermal reservoir. Because the wells generate only steam to run the turbines, no separation system is needed.

(b) **Single-double or triple flash systems:** In flash systems, the liquid flashes while still in the well. The steam enters the turbine and then the liquid is sent back to the reservoir. A double-flash steam plant is a modified version of the single-flash configuration, which can generate 15–20% more electricity for the same conditions. The capital, operating and maintenance costs of a double-flash system are more than single-flash systems, but the extra electricity produced often justifies the installation of these systems. Moreover, it has to be said that the efficiency of the flash cycles can be enhanced by adding one or two regenerators in order to recover internal heat rates. Furthermore, the proper design of the heat exchanging devices is important in order to reduce the exergy losses and to reduce the temperature difference between the heat streams.

(c) **Binary-cycle systems:** When low-grade geothermal energy is available, binary-cycle (indirect) systems are used. Generally, isobutane and pentafluoropropane are utilized as working fluids in these systems. The Kalina and organic Rankine cycles are commonly employed in binary systems. The thermal efficiency of binary systems is in the 10–13% range.

(d) **Flash/binary combined systems:** In flash/binary combined configurations, a hybrid form of binary and flash systems are employed. Fig. 1 illustrates the different configurations of geothermal power units [10].

1.2. *The organic Rankine cycle*

The organic Rankine cycle (ORC) is a power cycle that is ideal for low or medium-temperature heat sources. It is a usual technology for applications of lower capacity and thus it is commonly selected for applications with geothermal energy, solar energy, or waste heat recovery. ORC utilizes organic fluids as working fluids and thus it is able to choose the suitable working fluid which is suitable for every energy source. Practically, there is a need for achieving compatibility between the heat source temperature level and the saturation curve shape of the selected working medium. The critical temperature of the organic fluid is an important parameter and it has to be close to the temperature level of the heat source. In many cases, the regenerative ORC is used in order to utilize the waste heat at the exit of the turbine and to enhance the thermodynamic efficiency of the system.

The basic non-regenerative ORC is illustrated in Fig. 2. The system shown includes the heat recovery system (HRS) for inserting heat in the cycle, the expansion device (turbine) for work production, the condenser for rejecting heat to the ambient and the organic fluid pump. The minimum temperature approach between the geothermal source and the organic medium, the pinch point, is usually chosen to be between 5 °C and 20 °C [11,12].

Working fluid selection is important in designing the geothermal-driven ORC systems for high efficiency [13,14]. For a series circuit ORC system, organic working fluids with high critical temperatures like *iso*-pentane result in high efficiency, while for parallel circuits, fluids with low critical temperatures like R227ea are superior [15]. The traditional classification of the organic working fluids is according to the slope of the saturation vapor curve and so the fluids are separated into wet, dry and isentropic [16]. According to the Reference [16], the most suitable working fluids are the following:

Subcritical working fluids: R236ea, R600a, R600 and R245fa.
Superheated working fluids: R142b, R152a, R236ea, R600 and R600a.
Supercritical working fluids: R134a, R600a, R32 and R22.

On the other hand, a novel classification has also been suggested on the basis of the primary and secondary characteristic points on the same diagram. As many as 57 types of organic working fluids have been reported in [17]. Molecular degrees of freedom and the isochoric heat

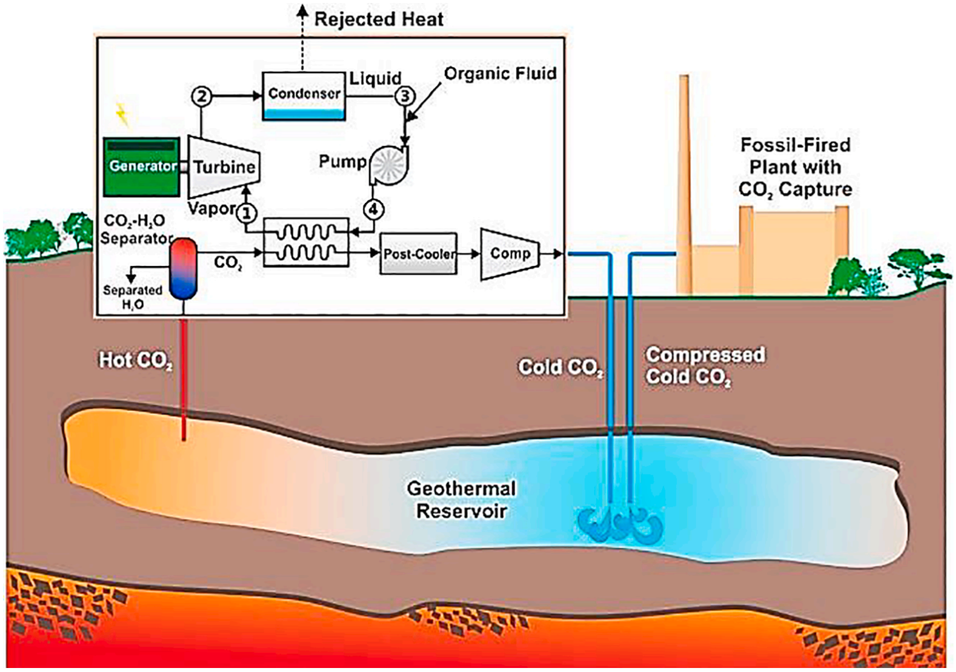


Fig. 3. Depiction of the investigated power system with geothermal reservoir [16]. (License Number: 5114781109141).

capacity have been used to pick out between the wet and dry type of organic working medium. It is shown that when the degree of freedom of molecules increases, the transition occurs from wet to dry type of organic fluid. [18] Zeotropic fluid mixtures are also widely used as working fluids in power generation systems. [19] Selecting an ORC working fluid is done by considering the system performance, chemical/physical properties of the fluid, like toxicity, flammability and environmental indexes like ozone depletion and global warming potentials. [20,21] Some of the hydrofluoroolefins such as R1234yf, R1225yeE and R245fa showed potential for low-temperature geothermal power applications as ORC fluids at geothermal heat source temperatures in the range 120 °C to 180 °C. [22]

1.3. Objectives of the present study

The current paper presents a detailed review in relation to the geothermal-fed ORC for electricity production. The review started by considering the performance analyses of geothermal-driven ORC systems. Both subcritical and supercritical ORC units are reviewed. Coupling the ORC systems with the Kalina cycle, absorption cycle and coal-fired gasification combined cycle are discussed. Both the energy and exergy analyses with different working fluids are reviewed. Also, experimental and numerical studies are considered in this review paper. Additionally, this review paper includes the techno-economic analyses of the geothermal-driven ORC systems. In this regard, the application of vapor absorption chiller, thermal energy storage and integration with natural gas expansion plant are discussed. In addition, optimization techniques of the ORC cycles are presented that included subcritical and supercritical ORC systems with and without regeneration and various types of working fluids using both the energy and exergy aspects. Furthermore, solar-geothermal hybrid ORC systems were considered. Various approaches for the optimization of such hybrid systems that included artificial intelligence are considered from the energy, exergy and power generation perspective. Moreover, it has to be said that studies about cogeneration, trigeneration and polygeneration systems that include ORC and geothermal energy are included in this review paper. The reviewed works are examined and discussed properly in order to determine the most effective choices. Tables are used in order to summarize the basic conclusions of all the studies. In the last part of this work, the most important conclusion is highlighted, the future steps in the field and given, as well as the challenges of the examined technology, are presented.

The novelty of this study is based on the detailed examination of the geothermal-driven ORC including different aspects such as experimental studies, numerical studies, energy, exergy and economical approaches. Moreover, the special novelty is the emphasis that is given in the use of geothermal ORC systems inside cogeneration, trigeneration and polygeneration units. This fact makes this review to be a novel one and to be different compared to the other published reviews in the existing literature.

2. Thermodynamic investigation of the geothermal-driven ORC systems

The performance analysis of geothermal-driven ORC systems has been considered by many researchers. The energy analysis and the performance investigation are essential for the proper evaluation of ORC systems. Various design and operational aspects of ORC systems together with different options of coupling them with other cycles have been considered to improve the efficiency of the geothermal-driven ORC units [23].

In this regard, Paloso and Mohanty [24] suggested the idea of coupling an absorption cycle to a geothermal-driven ORC system. They numerically investigated the application of an absorption heat-transformer (AHT) and a vapor-absorption chiller (VAC) to increase the temperature of the fluid fed to the ORC evaporator. The performance of three power generation cycles was compared including conventional ORC, AHT-ORC and VAC-ORC systems. They found the VAC-ORC system resulted in having the highest performance. Guzović et al. [25] investigated the potential of a geothermal-driven system such as an ORC or a Kalina cycle (KC) for power production in the Republic of Croatia. They assessed the suggested systems based on thermodynamic laws. They found that the ORC systems can be recommended because of high efficiencies. More specifically, the thermal performance of the ORC is 14.1% compared to 10.6% with the Kalina cycle, while the exergetic performance of the ORC is 52% compared to 44% with the Kalina cycle. Vetter et al. [11] compared the performance of a geothermal-driven ORC in subcritical and supercritical conditions for electricity

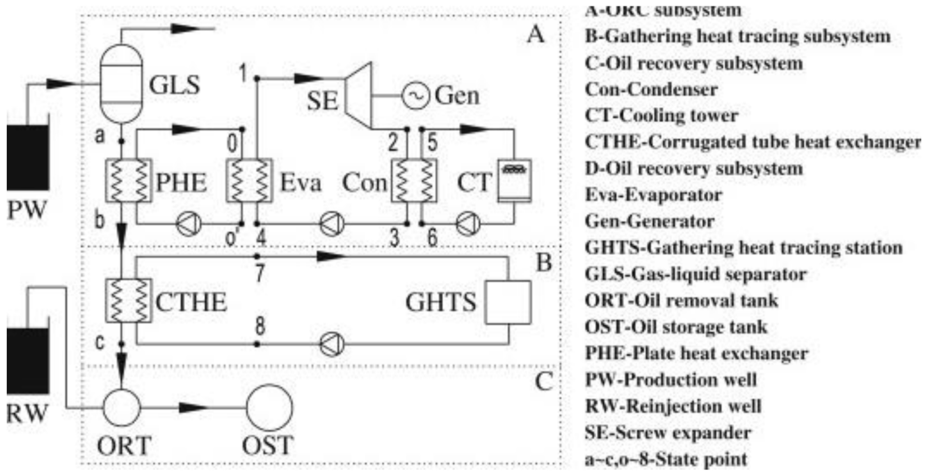


Fig. 4. Depiction of the electricity production unit with three subsystems and geothermal energy [30]. (License Number: 5114781431003).

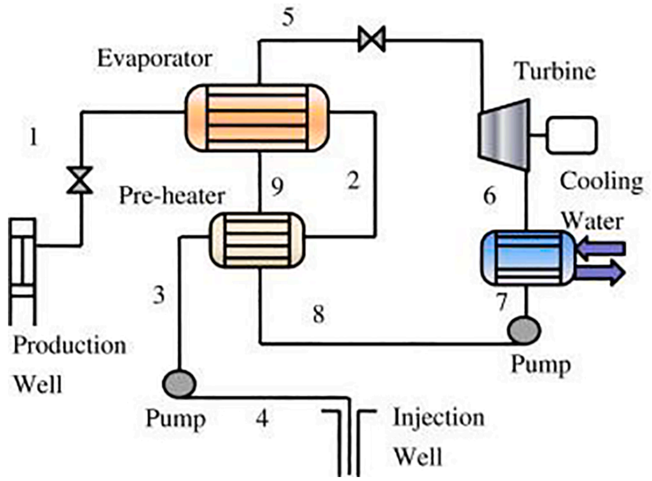


Fig. 5. Depiction of the investigated power generation system with a non-regenerative ORC [32]. (License Number: 5114790285167).

generation. Ten different refrigerants were considered in the organic Rankine cycle and it is concluded that propane or R143a can be suggested as an appropriate ORC working fluid at a geothermal temperature level of 150 °C. Sauret et al. [26] examined the performance of radial-inflow turbines in a geothermal-driven ORC system. Various ORC working fluids were evaluated including R134a, R143a, R236fa, R245fa and n-Pentane. They reported that the application of R134a and n-pentane resulted in the highest, and lowest performance of the system for power generation, respectively. Franco [27] investigated a geothermal-driven ORC unit for power production based on energy and exergy aspects. A regenerative ORC was investigated with water as the working medium between 100 °C and 130 °C. The performance of different organic Rankine cycle schemes was evaluated by testing different organic fluids including n-pentane, R134a, isobutane and R245fa. It was found that the regenerative configuration of the ORC decreased the brine-specific consumption of the unit. Besides, Kezemi and Samadi [28] compared the performance of four different types of geothermal-driven ORCs: basic ORC, regenerative ORC, two-stage evaporator ORC and the combination of the regenerative and two-stage evaporator ORC as the new ORC unit, from thermodynamic and economic points of view. It was found that the new ORC yielded the highest energy and exergy efficiency compared to the other types.

A typical geothermal-driven ORC system where CO_2 at supercritical conditions was used as the heat transfer MEDIUM of the geothermal energy is depicted in Fig. 3 [16].

A performance comparison for the geothermal-driven ORC and KC was done by Guzović et al. [29] based on the energy efficiency analysis. This study was conducted for a medium-temperature geothermal source

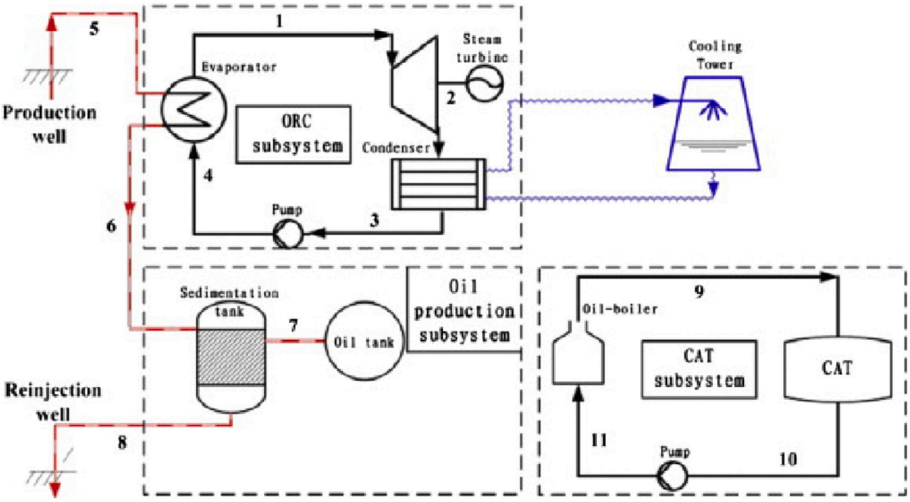


Fig. 6. Depiction of a system with ORC and oil production subsystem [33]. (License Number: 5114890732717).

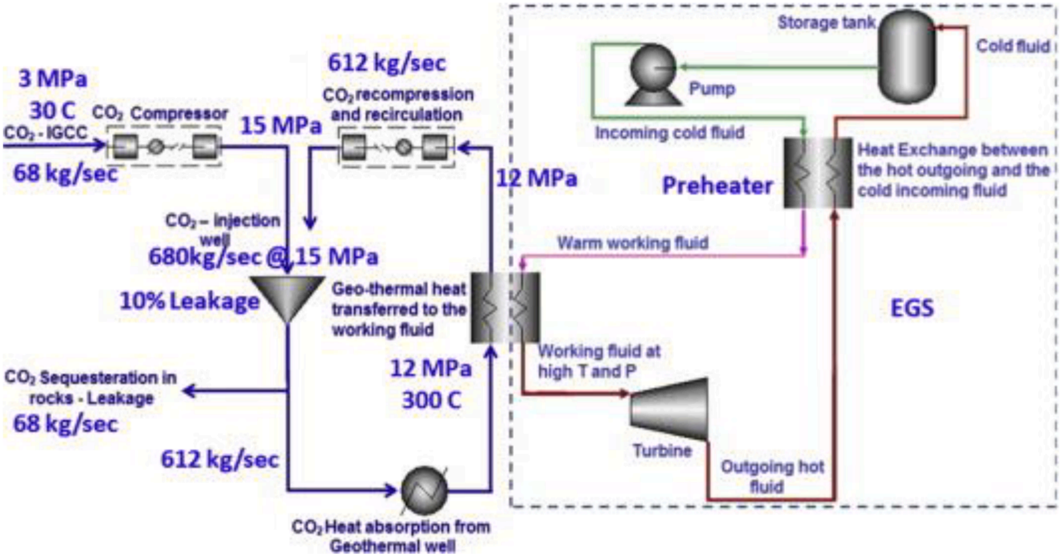


Fig. 7. A schematic view of an indirect geothermal power system [34]. (License Number: 5114890957090).

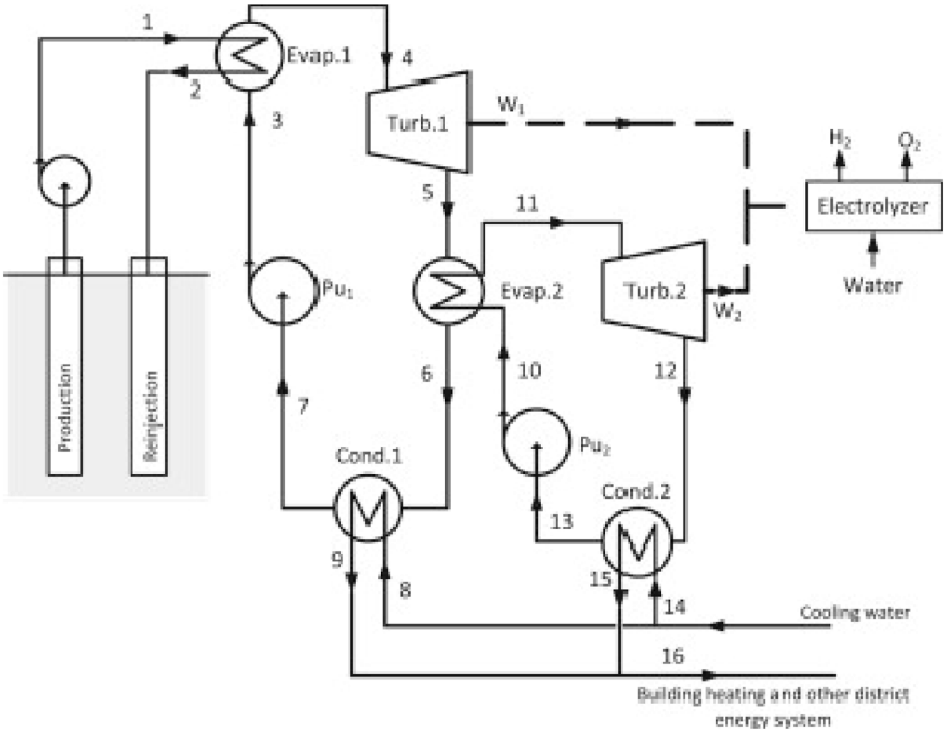


Fig. 8. A schematic view of a double-stage power generation system [35]. (License Number: 5114891216671).

in Lunjkovec-Kutnjak at 140 °C, as a case study in the Republic of Croatia. The ORC system showed higher thermal efficiency of 13.5% compared to the KC with a thermal efficiency of 12.8%. Gabbrielli et al. [30] conducted an investigation of the determination of the optimum operating conditions in the off-design operation for a geothermal-driven ORC by trying to maximize the cash flow. They found that the application of geothermal energy with the lowest temperature resulted in the best performance for a power generation unit. Li et al. [31] suggested an ORC combined with geothermal energy, gathering heat tracing and oil recovery systems. The depiction of the examined combined system is illustrated in Fig. 4. The suggested unit was combined with three subsystems. Different working fluids were studied for the ORC such as R245fa, R601a, R601, R141b, R123 and R600. It was calculated that the net power production was enhanced by 40% with the application of the optimized plant and R601a in the ORC.

Zhang and Jiang [32] thermodynamically investigated a geothermal-drive ORC system for power generation using different geothermal working fluid temperatures which are illustrated in Fig. 5. The impact of different ORC fluids was considered including isopentane, R134a, isobutane and R245fa. Also, three different types of power generation cycles were studied including subcritical, superheated and transcritical. It was reported that the transcritical cycle was determined as the best choice for reaching the highest performance. Fu et al. [33] compared the use of an organic Rankine cycle and a Kalina cycle coupled with a geothermal power unit in an oilfield and they studied different working fluids. The studied system is illustrated in Fig. 6 and the results showed

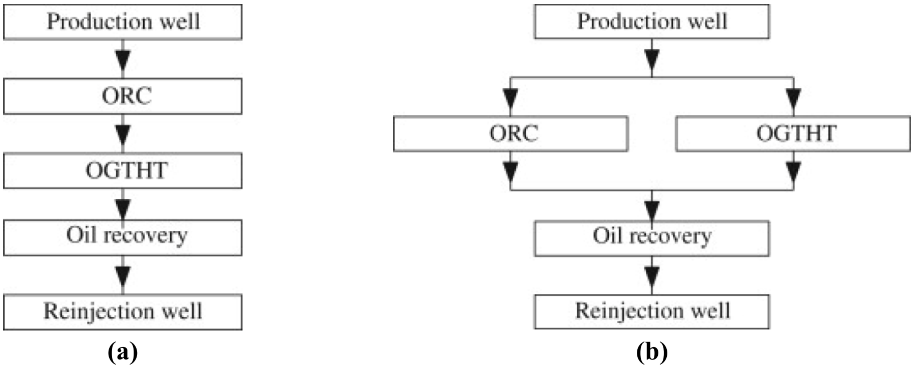


Fig. 9. A diagram view of the investigated systems by Ref. [37]. (License Number: 5114891467148).

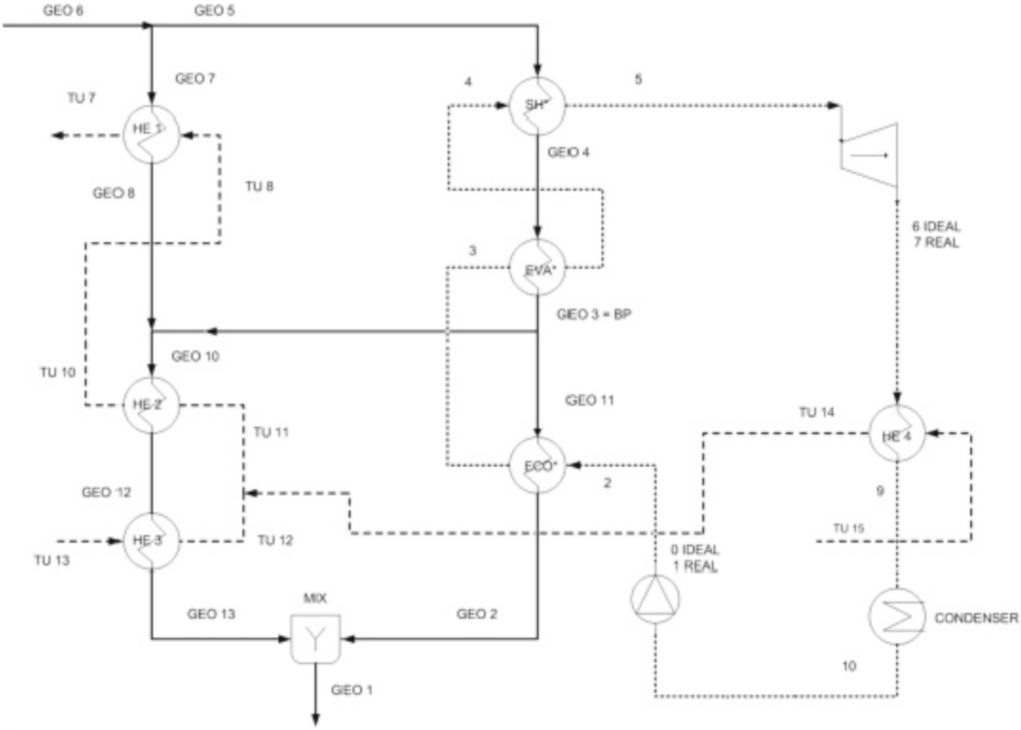


Fig. 10. A schematic view of the investigated system by Ref. [39] with details about the heat transfer devices. (License Number: 5114900308676).

that the application of R236fa leads to the highest performance of the ORC unit. Moreover, they clearly reported that the KC performed better than the ORC.

The performance of a geothermal-driven ORC unit using CO_2 as the HTF of the geothermal system was studied by Mohan et al. [34]. Fig. 7 depicts the examined system of this work with details. Four working fluids were investigated in the ORC including R134A, ammonia, n-Butane and neopentane. Among the investigated working fluids, ammonia showed the maximum power production of 49 MW_{el} with an efficiency of 23%. AlZaharani et al. [35] studied the energy and exergy performance of a Rankine cycle with CO_2 and R600. The system was assumed as a multi-generation system for electricity, heat and hydrogen production. The suggested systems were driven using geothermal energy as a medium–high temperature heat source and Fig. 8 shows the investigated system. The energetic efficiency and exergetic efficiency of the overall unit were reported at 13.67% and 32.27% respectively.

Configurations of the geothermal-driven ORC system for combined heating and power (CHP) were investigated by Habka and Ajib [36] based on energetic and exergetic aspects. The CHP system was investigated in parallel connection, series connection, and connection according to the Glewe-plant integration. R134a was applied as the ORC working medium. Their comparison concluded that the parallel connection is the best choice financially, while the optimum energy choice is the series connection. Li et al. [37] compared the performance of series and parallel circuits for heating, electricity and oil recovery for geothermal-driven ORC units. The studied series and parallel circuits of the investigated configuration are presented in Fig. 9. It was found that the series circuit is appropriate for high geothermal water inlet temperatures and low heat source inlet temperatures of the oil gathering and transportation heat tracing (OGTHT), while the parallel circuit is appropriate for low geothermal inlet temperatures and high heat source inlet temperatures of the OGTHT. Habka and Ajib [38] investigated a geothermal-driven ORC system based on power generation, heating, and cooling. R134a was selected as the ORC medium. According to the results, the power of the system reduced when there was an increase in the return temperature or in the heating demand. Also, they found improved energy and exergy efficiency of the unit when reducing the return temperature. Hsieh et al. [39] investigated the performance of a geothermal-driven ORC using a co-axial multi-tube heat exchanger. R-245fa was used as the organic fluid.

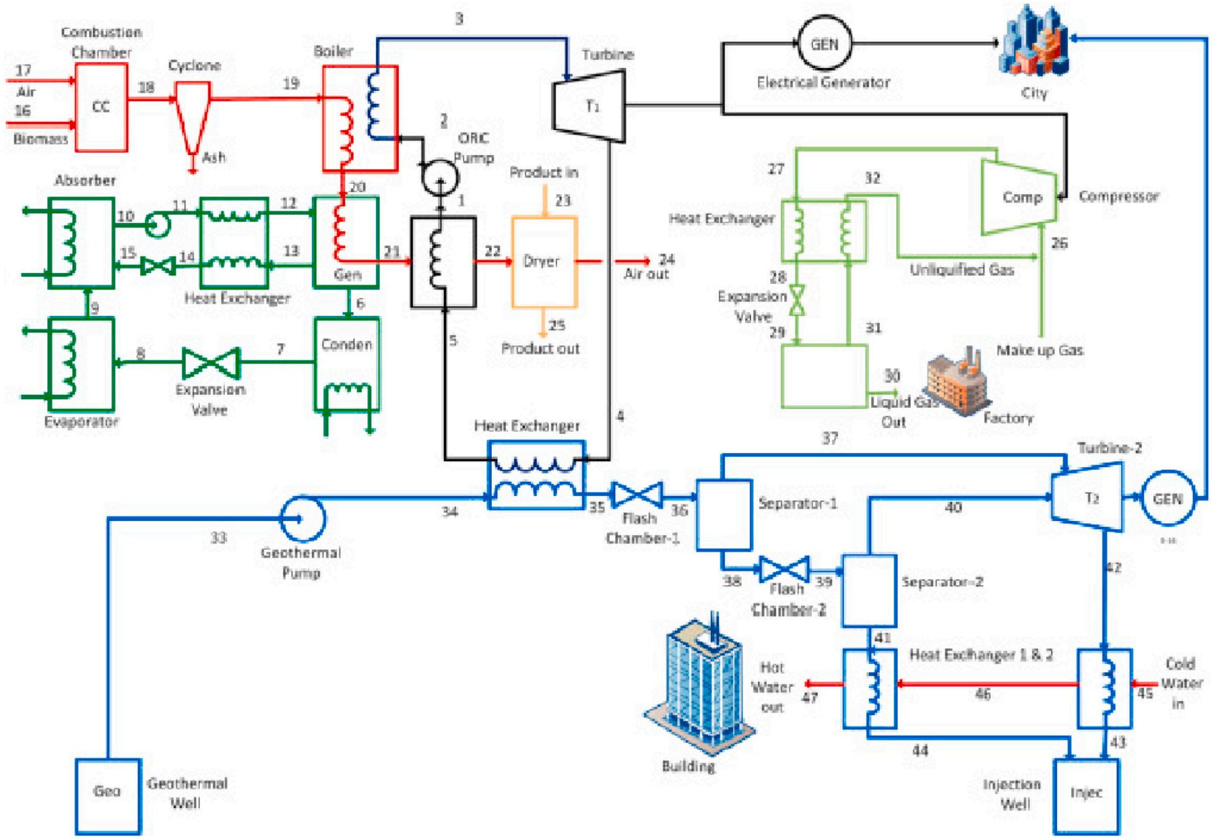


Fig. 11. A schematic view of a polygeneration system that uses geothermal energy for feeding two power cycles [45]. (License Number: 5114900577186).

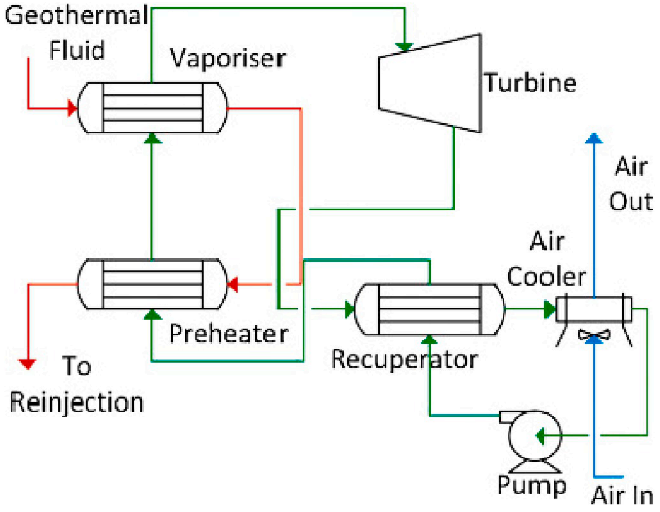


Fig. 12. A schematic of a regenerative ORC that exploits geothermal energy [46]. (License Number: 5114900878626).

Fiaschi et al. [40] suggested a new geothermal-driven ORC unit for the production of electricity and heat. The cross-parallel CHP system was proposed for the production of higher temperature heat for industrial applications. A depiction of the studied system is exhibited in Fig. 10. The system was developed for reducing the exergetic destruction in the heat exchanging surfaces and heat loss due to re-injection, to increase the energetic and exergetic efficiencies of the system. They found a 55% improvement in power generation of the suggested system compared to a conventional one.

Habka and Ajib [41] evaluated a geothermal-driven ORC using zeotropic mixtures as the working mediums. The unit was investigated based on parallel and series configurations for single power generation or CHP generation. Finally, it was concluded that the working fluids R22M, R422A and R438A were more efficient choices than the pure-fluids for the single electricity generation system. Similarly, the effect of using zeotropic mixtures (isobutene/is pentane and R227ea/R245fa) on the performance of an ORC unit run by low-enthalpy geothermal resources was identified by Heberle et al. [42]. The second law efficiency of the cycles were estimated according to the parameters such as the temperature of the heat source, the temperature difference of cooling water and the mixture composition. According to the result, when the temperature of the heat source was less than 120 °C, the second law efficiency rose by 4.3% to 15% for mixtures compared to the best pure working fluid. Specifically, a mixture whose temperature glide at the condensation matched the cooling water temperature difference showed the most efficient performance.

Liu et al. [43] evaluated the thermodynamic performance of a geothermal-driven ORC using zeotropic mixtures such as butane/pentane (R600/R601), butane/isopentane (R600/R601a), isobutane/pentane (R600a/R601) and isobutane/isopentane (R600a/R601a) as the working fluids. It was found that the maximum net power could be achieved at the higher mole fraction of the more volatile component on condition that the condensation temperature glide of the zeotropic mixture fitted with the increase in cooling water temperature.

A geothermal-driven ORC system for power generation coupled with an integrated coal-fired gasification combined cycle (IGCC) for providing the required CO_2 as the geothermal heat transfer fluid was studied by Mohan et al. [44]. They reported that the combination of a high-pressure turbine and an ORC was advantageous for power generation from the suggested system. Also, it was found that isobutene and isopentane were the ORC working fluids that generated the highest and lowest net EGS power over a period of 25 years. Malik et al. [45]

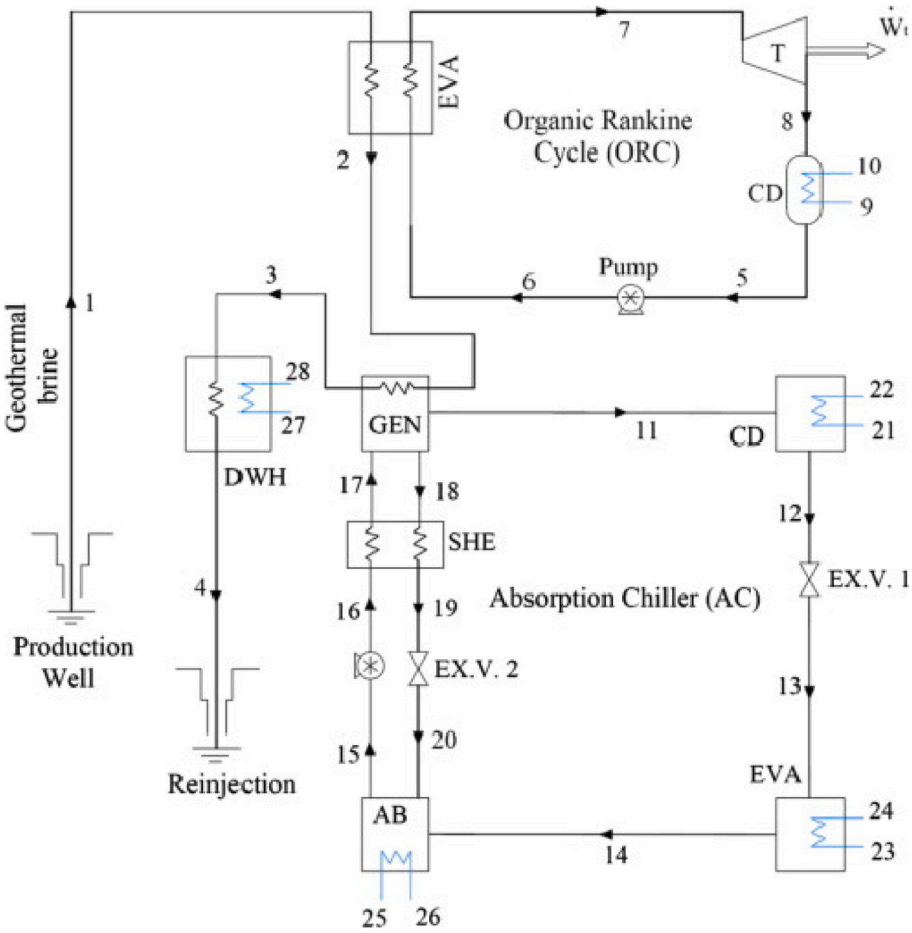


Fig. 13. A schematic view of a system with ORC and absorption chiller which is fed by a geothermal heat source [48]. (License Number: 5114901142247).

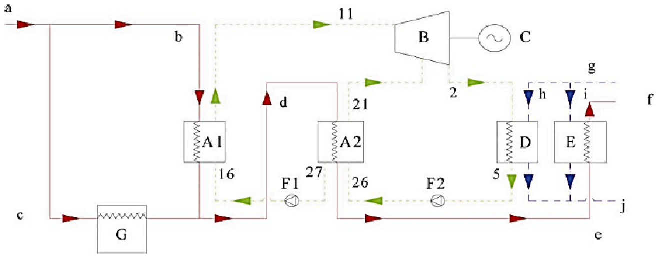
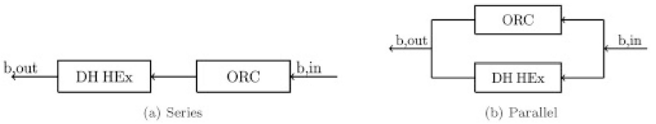


Fig. 14. Diagram of the studied power generation system by Ref. [50]. (License Number: 5114901339740).



(a) Series

(b) Parallel

Fig. 15. Depiction of the investigated series and parallel CHP cases by Ref. [52]. (License Number: 5114910030054).

energetically and exergetically investigated a geothermal/biomass-driven ORC system for electricity, cool production, heat production, gas liquefaction and air drying which is given in Fig. 11. They reported that the energy efficiency and the exergy efficiency of the unit were 56.5% and 20.3% respectively. Proctor et al. [46] dynamically simulated a geothermal-driven ORC for electricity production which is given in Fig. 12 and they validated their model with existing experimental data.

Performance optimization for the subcritical and supercritical ORC systems with single-stage axial flow turbines was done by Manente et al. [47]. The ORC unit was coupled with geothermal energy with a geothermal working fluid of 150 °C. They reported that the application of R1234yf, R134a, and R1234ze(E) was recommended as the optimum working fluids in the supercritical ORC system with the exergy efficiency in the range of 45.4% to 46.5%. Zare et al. [48] thermodynamically investigated geothermal-driven KC and ORC systems as multi-generation systems. The systems' performance was optimized according to the exergy efficiency criterion. A depiction of the investigated ORC unit is depicted in Fig. 13. According to the results, it is found that the KC system resulted in higher exergy efficiency compared to other investigated systems. It was found that the KC system with a heat source temperature of 120 °C, can generate 12.2% more electricity than the ORC system. An et al. [49] reviewed the application of geothermal energy for space heating and domestic hot water in Tianjin, China. Also, they presented a study for power generation with a geothermal-driven ORC system based on existing geothermal energy in Tianjin, China.

The performance of a two-stage serial ORC (TSORC) coupled with geothermal energy and absorption refrigeration (AR) is shown in Fig. 14 [50]. The integrated TSORC-AR system increases the net power compared to the TSORC system while decreasing the thermal efficiency of the generated power. Yuksel and Ozturk [51] suggested a geothermal energy-driven multi-generation system for electricity production using an ORC, domestic hot water, cooling using a quadruple effect absorption cooling system, and hydrogen using proton exchange-membrane electrolysis. They investigated the system based on energy and exergy analyses and reported energy and exergy efficiencies as 47% and 32.2%

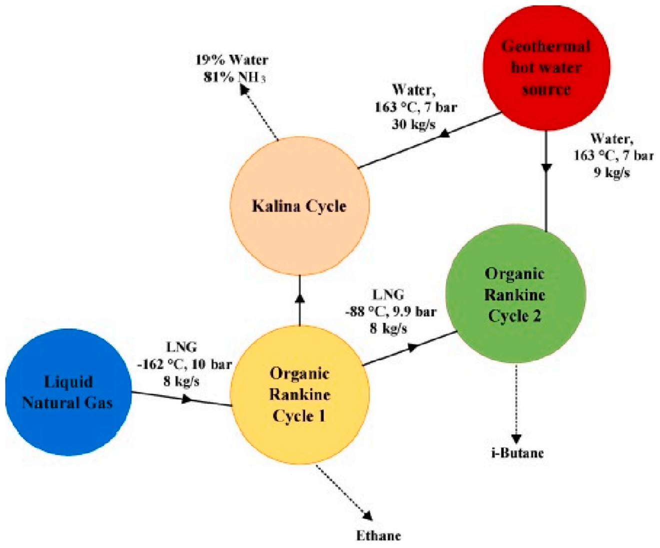


Fig. 16. Block-flow diagram of the power generation system by Ref. [53] which includes ORCs, Kalina cycle, geothermal reservoir and liquid natural gas. (License Number: 5114910219520).

respectively. They found increasing power generation from 4 MW to 8.5 MW, and increasing hydrogen production from 0.030 kg s^{-1} to 0.075 kg s^{-1} with the increase of geothermal fluid temperature from 130 °C to 200 °C.

Erdeweghe et al. [52] compared the exergy performance of the parallel and series configurations of a CHP plant coupled to 3rd and 4th generation thermal networks and Fig. 15 shows the examined configurations. The investigated systems were driven by geothermal energy and an ORC system was used for generating power. They found that the parallel and series configurations can be recommended for the high and low-temperature thermal networks, respectively. Exergy efficiency of the parallel configuration with a nominal heat demand of 6 MW was calculated as 41.25%. Sadaghiani et al. [53] suggested a combined electricity production plant including KC and ORC systems. Geothermal energy and liquid natural gas streams were used for converting heat to useful power. A block flow chart of the proposed power generation unit is presented in Fig. 16. The combined system was investigated based on energy and exergy aspects. The highest exergy efficiency of the system and the net power output of each unit were found at 32.15 kW and 2485 kW respectively. Li et al. [54] investigated a geothermal energy-based multi-generation system as shown in Fig. 17. The suggested system was including ORC units for electricity production. The impact of heat source and evaporator temperatures on the performance of the system was evaluated. The total energetic efficiency was reported as 75%.

The use of abandoned oil and gas wells with high temperatures as geothermal energy that can be used for electricity production was discussed by Nian and Cheng [55]. They presented different methods for utilizing geothermal energy for power generation including coupling with ORC systems. Also, a review was conducted on different methods for simulation of the heat transfer models of abandoned oil and gas wells geothermal systems. Akrami et al. [56] investigated a polygeneration unit based on a geothermal-driven ORC for power, heating, cooling and hydrogen production. The suggested configuration was analyzed according to energy and exergy aspects (Fig. 18). They found that the total energy efficiency and exergy efficiencies were 33.9% and 43.6%, respectively. Also, the net electricity production, hot water flow rate, cooling load and hydrogen production were calculated as 817 kW, 7.1 kg/s, 1900 kW and 0.05 g/s respectively.

The influence of accurate working fluid properties on predicting the optimum design of an ORC system was studied by Huster et al. [57]. They assumed a geothermal-driven ORC system. An artificial neural networks (ANNs) method was used for optimization. They concluded that the application of an accurate thermodynamic model is able to lead to the global optimum design, while the simplified models lead to non-optimal designs. Moreover, their methodology has a reasonable computation time which is an extra advantage. Karakilcik et al. [58]

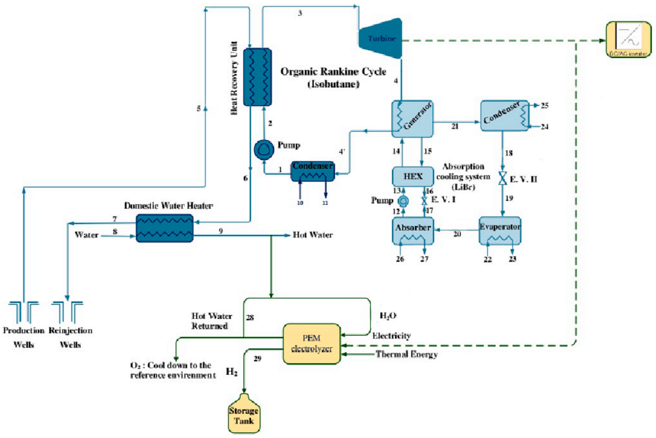


Fig. 18. A schematic view of a polygeneration system driven by geothermal energy [56]. (License number: 5114910650882).

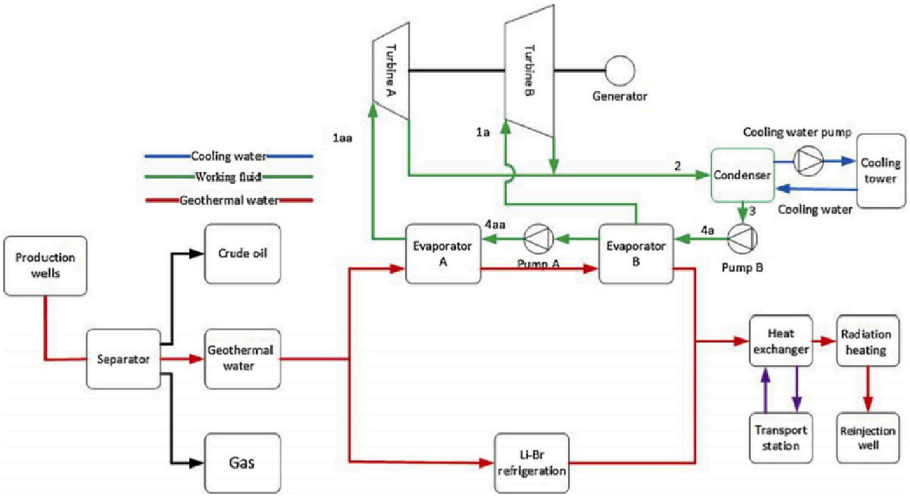


Fig. 17. A schematic view of the trigeneration system of Ref. [54]. (License Number: 5114910419600).

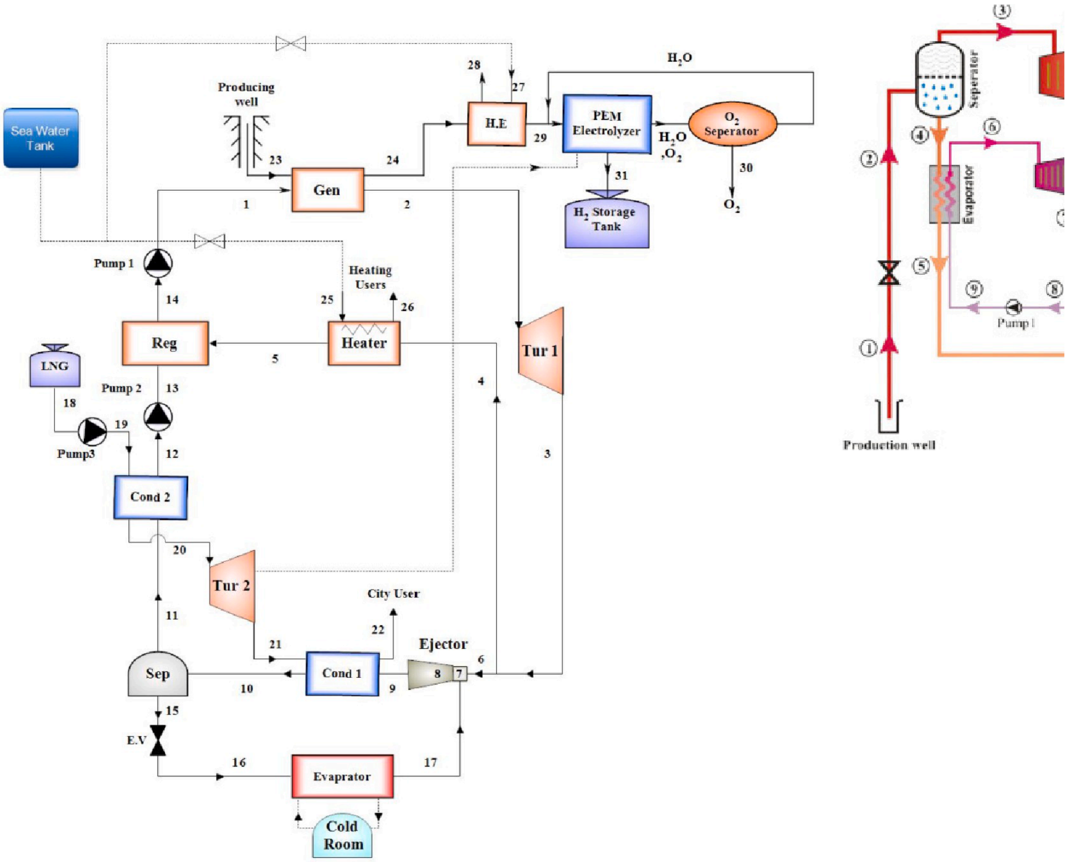


Fig. 19. A schematic view of a power generation system with direct and indirect cycles driven by a geothermal reservoir [58]. (License Number: 5114910917749).

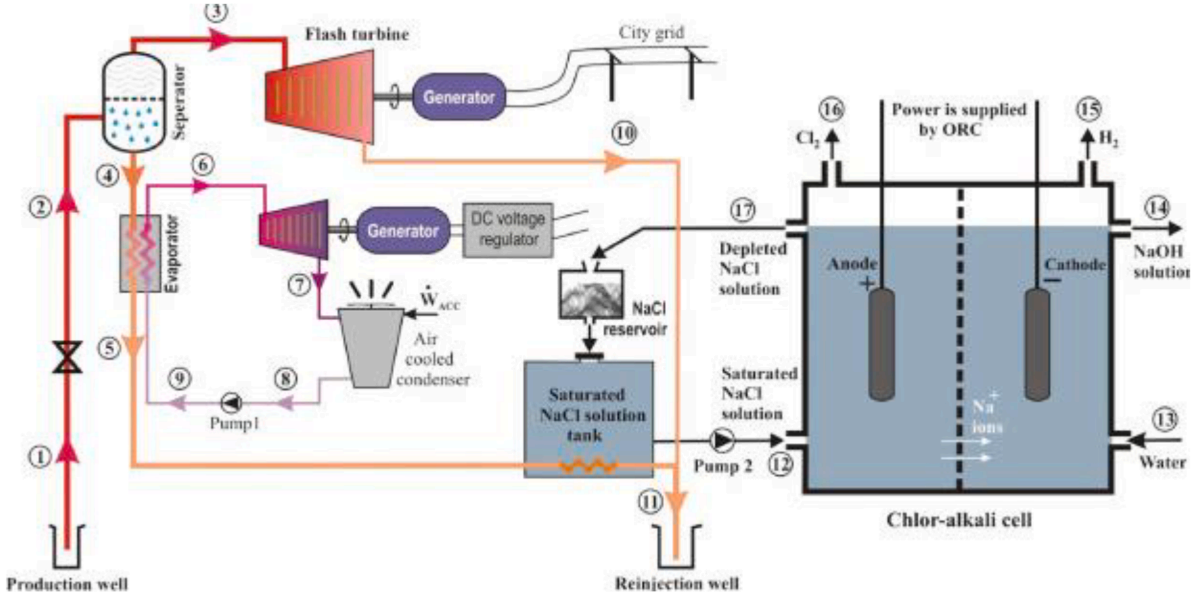


Fig. 20. A schematic view of a polygeneration unit driven by geothermal energy and LNG [59]. (License Number: 5114911275126).

investigated a polygeneration system for electricity and hydrogen generation using geothermal energy. An ORC system and a chlor-alkali cell were used for power, and hydrogen generation, respectively. A view of the investigated system is presented in Fig. 19. They found the electrical power generation improved from 2.5 to 3.9 MW and H_2 production increased from 10.5 to 21.1 kg/h, with increasing geothermal temperature between 140 °C and 155 °C. Also, the energy and exergy efficiency of the system was reported as 6.2%, and 22.4%, respectively, with a geothermal temperature of 155 °C. Ebadollahi et al. [59] suggested a new geothermal energy-based polygeneration system for cooling, heating, electricity and hydrogen production which includes an ORC and it is illustrated in Fig. 20. It is found that the energy efficiency to be 38.33% and the exergy efficiency to be 28.91%.

Performance investigation of a geothermal-driven ORC for electricity

Table 1
Summary of performance investigations of the geothermal-driven ORC system.

Study	Brief title	Highlights	Ref.
Paloso and Mohanty (1993)	Geothermal ORC and absorption chiller	The result of the numerical study showed that the system including VAC and ORC had the highest performance regarding the lower heat exchange area.	[24]
Guzović et al. (2010)	Electricity generation by geothermal energy	The ORC yielded 33.01% higher thermal efficiency and 18% higher exergy efficiency than the KC.	[25]
Sauret et al. (2011)	Radial-inflow turbines and high-density working fluids	R134a was the most appropriate working fluid for the described system.	[26]
Franco (2011)	A moderate temperature geothermal resource and ORCs	The author found that the regenerative configuration of the ORC system diminished the brine-specific consumption.	[27]
Heberle et al. (2012)	Zeotropic mixtures as working fluids in ORC	The zeotropic mixtures showed a better performance than pure working mediums on the condition that the heat source temperature was than 120 °C.	[42]
Guzović et al. (2012)	Electricity generation from medium-temperature geothermal sources	For a medium-temperature geothermal source, the ORC system showed better performance than the KC.	[29]
Gabbrielli et al. (2012)	A design approach for geothermal power plants	The use of geothermal energy with the lowest temperature resulted in the best operation.	[30]
Li et al. (2012)	Low-temperature geothermal water in oilfield power generation	By optimizing the plant and using R601a as the ORC working fluid, a 40% enhancement in power output was achieved.	[31]
Zhang and Jiang (2012)	Binary power cycle for different EGS geofluid temperature levels	The working fluids with critical temperatures close to the geofluid temperature present high efficiencies.	[32]
Vetter et al. (2013)	Sub- and supercritical ORC from low-temperature geothermal wells	To determine the working fluid for the geothermal power plant, the local geothermal fluid temperature and associated optimum critical temperature should be taken into consideration.	[11]
Fu et al. (2013)	A KC and ORC system based on coupling with geothermal power system	The KC performed better than the ORC system.	[33]
Mohan et al. (2013)	Carbon dioxide as a heat transfer fluid	Although ammonia yielded the highest performance, n-butane and neopentane could be considered as potential working fluids, considering the corrosive nature of ammonia.	[34]
AlZaharani et al. (2013)	A geothermal system for power, hydrogen and heat generation	The impact of various operational conditions, such as geothermal source temperature, ambient temperature and cooling water temperature, on the exergy and energy efficiency of each cycle, was considered.	[35]
Habka and Ajib (2013)	Operation characteristics for two configurations of heat and power systems	The parallel connection of ORC had a better economic performance while the series connection was more energy efficient.	[36]
Li et al. (2013)	Series and parallel geothermal systems in an oilfield	The parallel circuit was preferred for high geothermal water inlet temperatures and low heat source inlet temperatures of the OGTHT, while the opposite was preferred for the series circuit.	[37]
Habka and Ajib (2014)	Heating plant parameters and geothermal plant based on ORC	Dropping the return temperature by 5 °C increased the energy performance by 52% and the exergy performance by 9%.	[38]
Liu et al, (2014)	Effect of condensation temperature glide on the ORC	When the condensation temperature glide of the zeotropic mixture fitted with the rise in the temperature of the cooling water, the highest net power was obtained.	[43]
Hsieh et al. (2014)	A heat exchanger for a geothermal ORC	R-245fa was selected in the ORC.	[39]
Fiaschi et al. (2014)	An ORC power plant for heat and power generation	The cross-parallel CHP system showed a 51% improvement in power generation compared to the conventional one.	[40]
Habka and Ajib (2015)	An ORC with and without cogeneration	The zeotropic mixtures, R438A, R422A and R22M performed more efficiently in a single power generation system than pure working fluids.	[41]
Mohan et al. (2015)	CO_2-based EGS paired with IGCC for symbiotic integration of CO_2 sequestration	The integration of a high-pressure turbine and an ORC was recommended for power generation.	[44]
Malik et al. (2015)	An energy-based multi-generation system	The energy and exergy efficiencies of the geothermal cycle were reported as 64.2% and 50.9%, respectively.	[45]
Kazemi and Samadi (2016)	The optimization of a new geothermal ORC	The performance of a novel ORC unit consisting of regenerative and two-stage evaporator was investigated.	[28]
Proctor et al. (2016)	A commercial-scale geothermal ORC	The difference in power output between the dynamic model and the plant was 0.24%.	[46]
Manente et al. (2016)	Influence of the ORC turbine efficiency	The exergy efficiency of the supercritical ORC is the highest and ranges from 45.4% to 46.5%.	[47]
Zare et al. (2016)	A tri-generation system utilizing low-grade geothermal energy	The KC yielded higher exergy efficiency than other investigated systems.	[48]
An et al. (2016)	A hydrothermal geothermal resource in China	Flash and ORC are typically used in Tianjin to make the most of geothermal resources.	[49]
Sun et al. (2017)	TSORC integrated with AR for geothermal power generation	The geothermal heat source could be used more efficiently with the TSORC-AR compared to the solo TSORC.	[50]
Yuksel and Ozturk (2017)	A geothermal energy-based system for hydrogen production	The hydrogen production surged by 150% when the geothermal water temperature rose from 130 °C to 200 °C.	[51]
Erdeweghe et al. (2017)	Series and parallel configurations for a low-temperature CHP plant	The authors found that parallel configurations were more appropriate for high-temperature thermal networks, while series configurations were more appropriate for low-temperature networks.	[52]
Sadaghiani et al. (2018)	A geothermal-based plant with liquefied natural gas	The numerical study showed the potential of recovering energy from low-temperature heat sources like geothermal hot water.	[53]
Li et al. (2018)	Polygeneration system driven by geothermal water for oilfield	The output power of the ORC increased by about 300% when the heat source temperature increased from 110 to 115 °C.	[54]
Nian and Cheng (2018)	Geothermal utilization of abandoned oil and gas wells	ORC systems were identified as a promising method to exploit oil and gas wells with high temperatures as geothermal energy.	[55]
Akrami et al. (2018)	An analysis of a multi-generation energy system	The parametric analysis indicated that a rise in absorber operating temperature, turbine inlet temperature and pressure improved the total exergy efficiency.	[56]
Huster et al. (2019)	Impact of accurate working fluid properties on an ORC	ANNs method indicated the importance of the accuracy of the thermodynamic model on design decisions.	[57]
Karakilcik et al. (2019)	A chlor-alkali cell integrated into a geothermal resource	A positive effect on hydrogen production was observed for an increase in the geothermal resource temperature.	[58]
Ebadollahi et al. (2019)	A geothermal-based multigeneration system using energy recovery	The prices of the heating capacity, cooling capacity, net output power, and hydrogen were estimated to be 480.1 $/GJ, 441.8 $/GJ, 292.4 $/GJ, and 409.4 $/GJ, respectively.	[59]

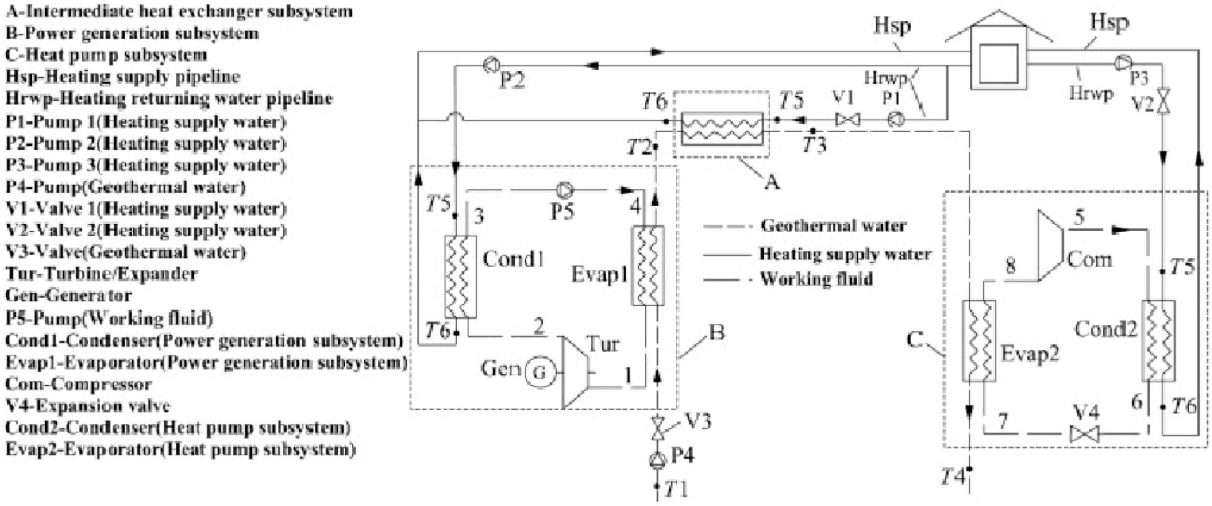


Fig. 21. Depiction of the investigated cogeneration system by Ref. [66]. (License Number: 5114911506092).

production was also considered in Refs. [60,61]. Bronicki [62] conducted a review associated with different existing geothermal cites for power generation with the ORC system up until 1988. Vonsée et al. [63] presented an assessment framework of technology dependence for geothermal power based on the ORC system in the European Union. Bonalumi et al. [64] investigated geothermal-driven ORC and flash technologies for power generation. They reported that higher performance could be obtained with the application of supercritical plants with a recuperative layout for the ORC system.

A summary of the performance investigations of the geothermal-driven ORC system is presented in Table 1. It can be said that the ORC leads to higher efficiency than the cases with the Kalina cycle. Moreover, it is found that natural refrigerants are very promising choices for ORCs. Also, it is useful to state that the parallel configuration is more efficient than the series one, as well as the increase in the geothermal temperature level, enhances significantly the unit performance.

3. Techno-economic analyses of geothermal-driven ORC systems

The financial aspects are very important in order to determine the viability of the ORC systems. Mohanty and Paloso Jr [65] economically examined a geothermal-driven ORC configuration with the application of a vapor absorption chiller (VAC) for increasing power generation compared to the conventional ORC system. They found that the ORC-VAC system can be recommended as a more economical system for power generation. Guo et al. [66] techno-economically evaluated a geothermal-driven ORC system as a cogeneration system which is given in Fig. 21. They investigated different ORC working fluids and cycle parameters for the optimization performance of the system. They reported that E170, R600 and R141b showed better performances comprehensively. Vélez et al. [67] studied the low to medium-temperature heat sources that were connected to the organic Rankine cycle for power generation. They reviewed ORC systems based on technical and financial aspects as well as market evolution. This review showed that an ORC plant was a proven technology to harvest low-enthalpy geothermal sources. In this case, the capacity of commercial standard modules varied between 300 and 1200 kW with the installation costs ranging from 1000 to 4000 €/kWe. Eyidogan et al. [68] performed a techno-economic analysis on ORC power cycles coupled with low-temperature heat sources. It was reported that the investment payback period of an ORC with a biomass-driven system was calculated as 2.7 years for the generation of 1 MW power.

The application of thermal energy storage in an ORC unit coupled with a low-temperature heat source such as geothermal based on techno-economic aspects were investigated by Rodríguez et al. [69]. A transient model was developed for a 1 MW ORC power plant using energy storage technology. Numerical results were validated with experimental results. Fiaschi et al. [70] numerically compared the performance between two power generation cycles including ORC and KC based on geothermal-driven systems. Two different geothermal sites including Mount Amiata, Italy with a heat source of 212 °C, and Pomarance, Italy with a heat reservoir of 120 °C were investigated. The suggested systems were assessed based on energy, and exergoeconomic aspects. They found that the KC can be recommended as the most efficient cycle, producing 22% to 42% more net power than ORC systems for the low-temperature heat source. Also, the cost of the electricity was estimated at 12.5 c€/kWh. On the other hand, the ORC with R1233zd(E) had resulted in the best exergoeconomic performance for the medium-temperature heat source. Akrami et al. [71] developed a geothermal-driven system in which an ORC system was used for the generation of electricity which is depicted in Fig. 22. The system was analyzed in energy, exergy, and exergoeconomic aspects. The impact of different parameters on the system's performance was investigated. It was found that the energy efficiency and the exergetic efficiency of the suggested system were found at 35.0% and 49.2% respectively. Furthermore, the highest and the lowest total unit costs of the products were reported as 23.18 $/GJ and 22.73 $/GJ for the geothermal water temperatures of 185 °C, and 215 °C respectively. Likewise, the exergetic and energetic performance of a geothermal-driven ORC was studied by El-Emam and Dincer [72]. The ORC working fluid was isobutene and the temperature of the geothermal water at the optimal point was considered 165 °C. Under such conditions, the energy and exergy efficiency of the unit were computed as 16.37% and 48.8%, respectively.

A geothermal-driven power generation system was optimized by Aali et al. [73] using single and multi-objective optimization using the existing data from the Sabalan geothermal field, Iran. The system was analyzed using energy, exergy, and exergo-economic analyses as shown in Fig. 23. They found that exergy efficiency and specific cost of output power were found at 52.56% and 4.901 $/GJ, based on single-objective optimization, and 54.87% and 5.068 $/GJ based on multi-objective optimization, respectively. Yao et al. [74] economically and thermodynamically investigated a novel integration of a natural gas expansion plant with a geothermal-driven ORC technology as Fig. 24 indicates. The fluid in the ORC was R600 and they conducted a multi-objective optimization using the TOPSIS decision-making method for finding the optimal evaporator temperature. The energetic and exergetic efficiencies of the optimized configuration were calculated at 89.8% and 84.13% respectively, with the optimum evaporator temperature of

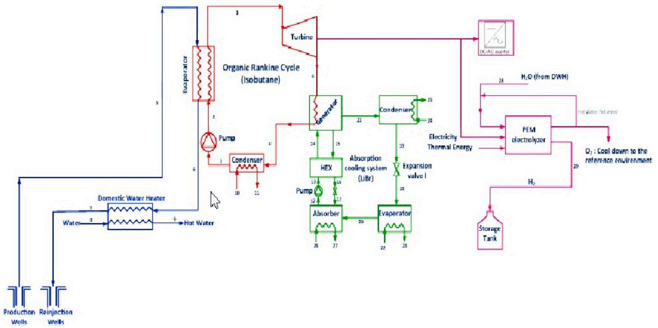


Fig. 22. A schematic view of a polygeneration system driven by geothermal energy [71]. (License Number: 5114920223720).

45.5 °C. Furthermore, they expected a net profit of 3.97 M$ during the lifetime of the plant and a payback period of 2 years for the optimized power generation system.

A polygeneration system for generating electricity, hot water, and pure water based on a geothermal-driven unit was suggested by Behnam et al. [75] and it is shown in Fig. 25. The system was investigated based on energetic, exergetic and thermo-economical aspects and geothermal water at 100 °C. The freshwater production capacity was calculated at 0.662 kg/s. They obtained 161.5 kW electricity and 246 kW heating. Kahraman et al. [76] numerically investigated a geothermal-driven ORC system based on thermodynamic and economic aspects. They investigated the influence of ambient temperature on the energy and exergy performance of the ORC system. They concluded that the power generation reduced to about 6.8 MW as the ambient temperature increases from 5 °C to 35 °C, whereas first thermodynamic law efficiency and the thermodynamic law efficiency are decreased from 13.7% to 9.2% and 54.9% to 36.7% respectively, with increasing ambient temperature from 5 °C to 35 °C respectively.

Fraia et al. [77] presented a novel geothermal-driven ORC system for providing electricity and heat by wastewater and sludge treatment. They investigated the suggested system of Fig. 26 according to energetic, exergetic and economical points of view. They reported a reduction in sludge disposal by 70%. Also, they found a payback period of around 5 years and CO_2 equivalent emissions savings of 628 tons per year. Meng et al. [78] studied the techno-economic performance of four different configurations of a geothermal-driven ORC system for the generation of power and heat. Four suggested systems were optimized based on the evaporation temperature and flash temperature. They found that the double-flash ORC yielded a levelized cost of electricity of 0.0831 $/kWh and a payback period of 9.43 years. Fig. 27 shows the examined configuration of the geothermal-driven power unit. Tartiere et al. [79] considered the coupling of a novel cooling system to a geothermal ORC, which showed a noticeable increase in power generation and profit. Most recently, Li et al. [80] showed that a multi-generation system for oilfields, which includes ORC power generation, heating, refrigeration, as well as other oilfield processes, can have a payback period of about 3 years.

A summary in relation to the techno-economic analyses of the geothermal-driven ORC systems is presented in Table 2. The financial investigation of the geothermal-based ORC systems is very important in order to determine their viability. According to the revised studies, the payback period of the investments can be ranged from 2 years up to 9

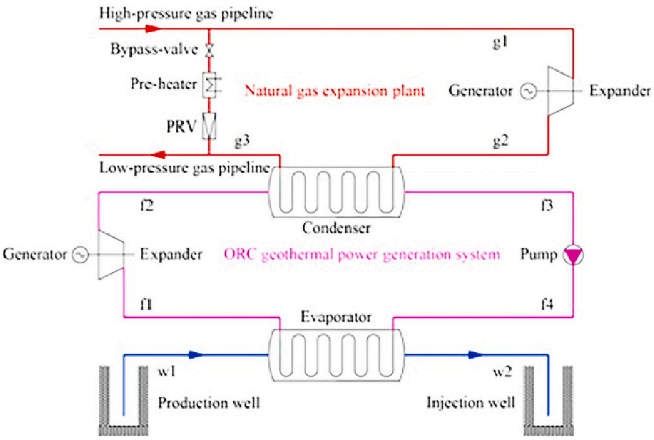


Fig. 24. A schematic diagram of a power system with a geothermal sink coupled to the condenser [74]. (License Number: 5114920641943).

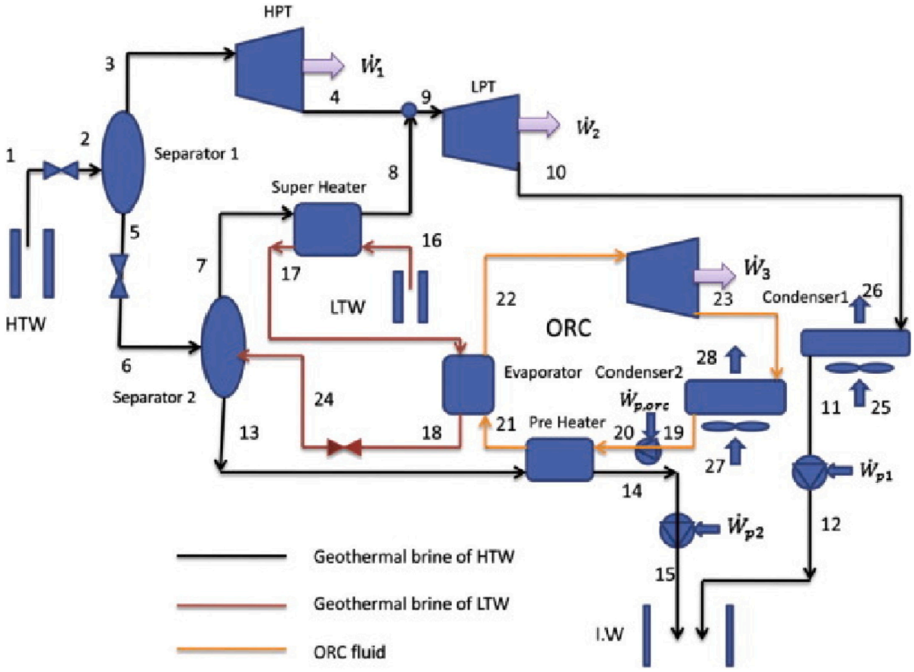


Fig. 23. A schematic view of a power system with direct and indirect cycles driven by geothermal energy [73]. (License Number: 5114920430088).

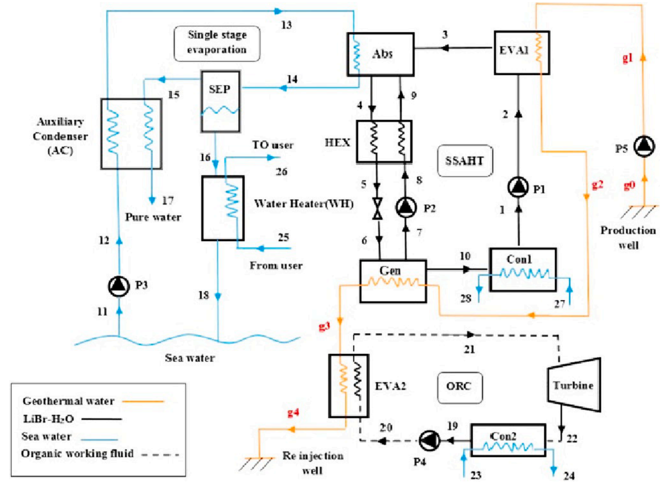


Fig. 25. A schematic view of a power system that exploits geothermal energy and the sea water reservoir [75]. (License Number: 5114920850847).

years which leads to viable investments. Moreover, in the cases of polygeneration, the payback period is usually lower, the fact that indicates this idea as an ideal one from the financial point of view.

4. Experimental studies of geothermal-driven ORC systems

The experimental investigations were done to study the performance of the geothermal-driven ORC and to determine the limitations and the difficulties of this technology. Tang et al. [81] investigated the impact of twin-screw expander application in geothermal-driven ORC systems for electricity experimentally, as it is shown in Fig. 28. The influence of various parameters was considered on the performance of the expander. The numerical model they developed was also validated from the experimental tests. They reported the energy efficiency of the ORC system at 7.5%. Yang et al. [82] designed a geothermal-driven ORC system for power generation from abandoned oil wells in the Huabei oilfield of China. The fluid R245fa was selected in the ORC and Fig. 29 illustrates the studied configuration. The final results showed an efficiency of 78.52 % for the suggested turbine and an ORC efficiency of 5.33% based on experimental investigations.

Hu et al. [83] designed and experimentally tested a geothermal-driven ORC system under partial load conditions. A 500 kW ORC with R245fa was investigated. The analyses were conducted for a case study at the Huabei oilfield, China. They found that the geothermal water flow rate had an impact on the parameters' stability in the ORC unit. In detail, instability in the geothermal water flow rate brought about great fluctuations in the evaporator and turbine inlet and outlet pressure, the temperature of the hot water and the power output. Wang et al. [84] experimentally investigated a new variable electricity capacity based on a geothermal-driven flash-ORC system. They proposed this system due to the variable temperature of the geothermal energy during a typical day, as well as in different seasons. The system was evaluated at both steady and dynamic conditions. The maximum net electricity production of the ORC subsystem was 0.74 kW in steady-state conditions. Also, it was reported that power generation increased with decreasing the load.

An experimental investigation for an ORC unit for power generation was done by Song et al. [85]. A photograph of their experimental setup is illustrated in Fig. 30. Two scenarios were considered for coupling the ORC system: geothermal energy only or hybrid system with solar irradiation and geothermal energy. Thermodynamic modeling was conducted using MATLAB software. Variation of solar radiation and ambient temperature was investigated. They found 11.21% higher energy efficiency of the hybrid-driven ORC unit compared to the single geothermal-driven ORC system for power generation. Lin et al. [86] experimentally investigated the energetic behavior of a 10 kW ORC that was driven with a low-temperature heat source such as geothermal. The fluid R245fa was used in the ORC and the total configuration is given in Fig. 31. They concluded that the net thermal efficiency was 8.9%, while the net electricity efficiency was 7.9%.

Chao et al. [87] experimentally investigated a geothermal-driven flash-ORC for electricity and they gave the emphasis on the optimization of the working fluid (R245fa) mass flow rate. Chaiyat et al. [88] studied the CCHP of Fig. 32 based on levelized energy and exergy costs in a life cycle evaluation. The suggested unit was driven by geothermal energy. Also, an ORC system with R-245fa was used for electricity production. They concluded that the energetic and exergetic outputs of the CCHP unit were equal to 32.62 kWh and 6.98 kWh with mean efficiencies of 11.6% and 11.2% respectively. Also, it was stated that the levelized energy and exergy costs were calculated as 0.069 $/kWh and 0.323 $/kWh, respectively. Welzl et al. [89] conducted some experimental tests of nucleate pool boiling heat transfer coefficients in an evaporator of a geothermal-driven ORC system for power generation. Two organic fluids were investigated including R245fa, and R1233zd

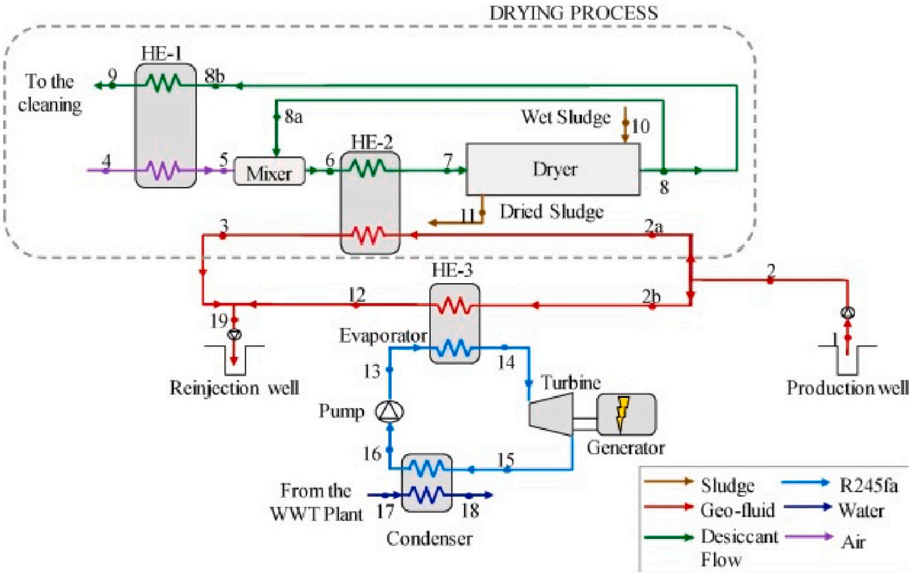


Fig. 26. Depiction of a cogeneration system driven by geothermal energy [77]. (License Number: 5114921014246).

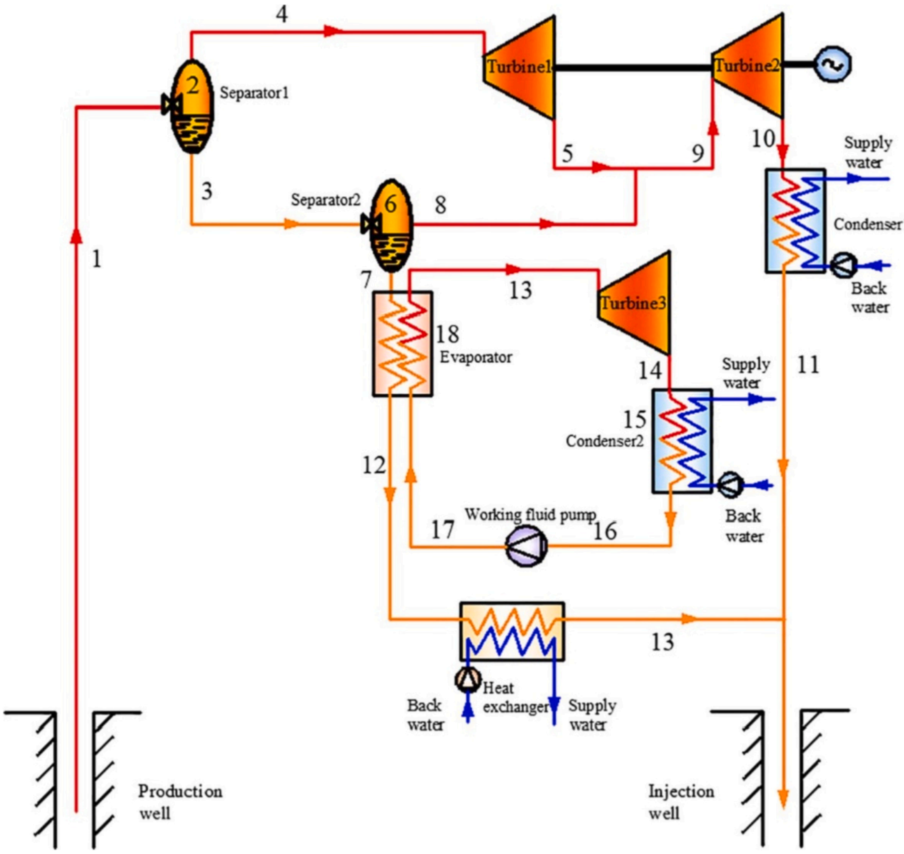


Fig. 27. A schematic view of a power system with primary and secondary cycle driven by a geothermal well [78]. (License Number: 5114921362157).

(E). They concluded that R245fa had higher heat transfer characteristics of up to 43.2% compared to R1233zd(E). Also, the electricity production of the ORC system with R245fa resulted in higher power output compared to the application of R1233zd(E). Experimental investigations on a geothermal-driven ORC system were also conducted in Ref. [90].

A summary of experimental works related to performance investigation of geothermal-driven ORC systems based is presented in Table 3. The experimental investigations are very useful in order to determine difficulties and limitations during the system operation. Usually, the obtained efficiencies are lower compared to the theoretical studies due to the use of pilot units and the use of low-scale devices. Moreover, the experimental studies can examine the systems during partial load conditions and during dynamic operation.

5. Optimization of the geothermal-driven ORC systems

Optimization is important for the proper design of the systems in order to have high energy performance and to be financially viable. Hettiarachchi et al. [91] optimized a geothermal-driven ORC system. They used the steepest descent method for optimization. Different parameters were investigated in the optimization study including the evaporator and condenser temperature levels, and the water velocity. Furthermore, the influence of different organic fluids was investigated including ammonia, R123, n-pentane and PF5050. Based on exergy analysis, they concluded that in the optimization process the efficiency was more compromised for ammonia than for the other working fluids. Shengjun et al. [92] examined the performance of a geothermal-driven ORC system based on a subcritical and transcritical cycle. They reported that the application of R123 in a subcritical ORC system was recommended for reaching the highest energetic and exergetic efficiencies of 11.1% and 54.1% respectively. Also, the application of R125 as the ORC working fluid was reported as the most cost-effective approach in the transcritical power cycle.

Generally, the performance of the geothermal-driven ORC depends on the heat source and the sink temperatures. Consequently, the performance of the ORC system varies with the change of the ambient temperature. Manente et al. [93] created an off-design model for optimum power generation with the variation of ambient temperatures from 0 °C to 30 °C and geo-fluid temperatures from 130 °C to 180 °C. Garg et al. [94] examined the application of isopentane, R-245fa and their mixtures (in 0.7 / 0.3 mol fraction) as the working medium of an ORC with low-temperature level heat sources such as solar or geothermal (see Fig. 33). They reported an optimum energy efficiency of about 13% with turbine expansion ratios in the range of 7 to 10. M

The thermodynamic performance optimization of an ORC unit connected to a medium-temperature heat source such as geothermal energy was carried out Maraver et al. [95]. They presented guidelines for the optimization of subcritical and transcritical ORC units with or without regeneration. Different ORC operating mediums were investigated including Toluene, R245fa, n-Pentane, Solkatherm, R134a and Octamethyltrisiloxane. Liu et al. [96] optimized the performance of a geothermal-driven ORC for isobutane/isopentane (R600a/R601a) mixtures as the ORC organic fluid which is illustrated in Fig. 34. The optimization was done for various mole fractions of R600a/R601a mixtures. Also, the influence of geothermal water temperature levels of 110 °C, 130 °C and 150 °C was considered. With the application of an R600a/R601 mixture, an increased power generation of 11% was reported for geothermal water temperature levels of 110 °C when compared to using pure R600a. The maximum power generation was found when using R600a at a mole fraction of about 0.9.

A two-stage series ORC (TSORC) coupled with a low-grade heat source such as geothermal energy as shown in Fig. 35 was optimized by Li et al. [97]. They found that the TSORC is more preferable to an ORC for electricity production. Sadeghi et al. [98] energetically and

Table 2

Summary for techno-economic analyses of the geothermal-driven ORC system.

Study	Brief title	Highlights	Ref.
Mohanty and Paloso Jr (1992)	Power generation using ORC and geothermal-driven ORC system for power generation	The ORC-VAC system was a more cost-effective system than the solo system.	[65]
Guo et al. (2011)	A cogeneration system driven by low-temperature geothermal sources	E170, R600 and R141b were introduced as suitable working fluids resulting in a promising performance of the unit.	[66]
Vélez et al. (2012)	A review of ORCs for the conversion of low-grade heat	ORCs supplied output power ranging from 0.2 MWe to 2 MWe with a cost of 1000 €/kW$_{el}$ to 4000 €/kW$_{el}$.	[67]
El-Emam and Dincer (2013)	Exergoeconomic analyses of geothermal ORC	The energy and exergy efficiencies of the proposed unit were calculated as 16.37% and 48.8%, respectively.	[72]
Eyidogan et al. (2016)	ORC technologies in Turkey	The potential of low-temperature heat sources such as geothermal, solar energy, biomass and waste heat for feeding an ORC were considered.	[68]
Rodríguez et al. (2016)	Thermal energy storage solutions for a CSP-ORC plant	The possibility of the usage of thermal energy storage in an ORC unit joined with a low-temperature heat source was considered.	[69]
Fiaschi et al. (2017)	An ORC and KC to exploit low and medium–high temperature geothermal sites	The KC was found to be a better system than the ORC to exploit low-temperature geothermal heat sources.	[70]
Akrami et al. (2017)	A polygeneration energy system based on geothermal energy	The highest and lowest cost of the products was calculated as 23.18 $/GJ and 22.73 $/GJ for geothermal water temperatures of 185 °C and 215 °C, respectively.	[71]
Aali et al. (2017)	Optimization of a flash-binary cycle	A 3.4% difference between the specific cost of the output power achieved by single and multi-objective optimization methods was observed.	[73]
Yao et al. (2018)	A geothermal system integrating a natural gas expansion plant	Energy and exergy efficiencies of the optimized system were calculated as 89.8% and 84.13% by the TOPSIS decision-making method.	[74]
Behnam et al. (2018)	A tri-generation system driven by low-temperature geothermal sources	The system produced 0.662 kg/s of fresh water, 161.5 kW of power, and 246 kW of heat.	[75]
Kahraman et al. (2019)	A 21 MW geothermal plant and the effect of ambient temperature	It was observed that the ambient temperature had a considerable impact on the energy and exergy efficiencies of the system.	[76]
Fraia et al. (2019)	A geothermal based unit for wastewater and sludge treatment	The unit contributed to saving CO$_2$ equivalent emissions of 628 tons per year.	[77]
Meng et al. (2020)	Enhanced geothermal system	The levelized cost of electricity generated by the optimized double-flash ORC was 0.0831 $/kWh.	[78]

Fig. 28. A photograph of the examined experimental setup by Ref. [81]. (License Number: 5115141490932).

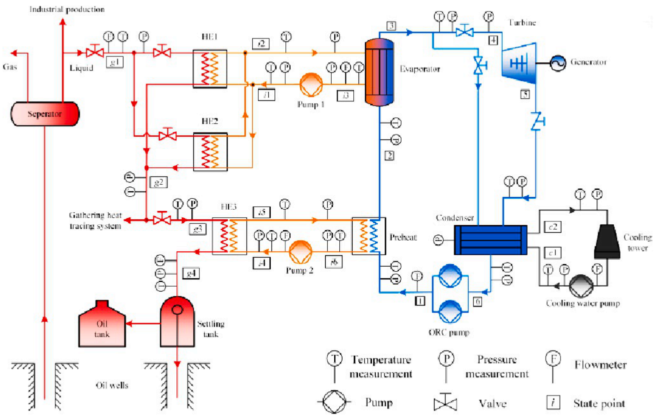


Fig. 29. Depiction of the suggested geothermal ORC system by Ref. [82]. (License Number: 5115150177572).

exegetically optimized three different cases of geothermal-driven ORC units for electricity production using zeotropic mixtures. The investigated configurations included the ordinary ORC, PTORC and TSORC, as they are presented in Fig. 36. They concluded that power generation of the simple ORC, PTORC and TSORC improved with 27.76%, 24.98% and 24.79% with the application of the zeotropic mixtures, respectively.

Karimi and Mansouri [99] optimized the performance of three different kinds of ORC systems, namely a basic ORC, a regenerative ORC and a two-stage evaporation ORC. Decision variables such as pinch point temperature difference in the evaporator, superheat degree, and the temperatures of evaporator and regenerative were varied in order to achieve the maximum exergy efficiency and minimum specific investment cost. According to the results, two-stage evaporation ORC yielded the maximum electricity generation rate. Also, the maximum and minimum levelized cost of energy were 0.1474 $/kWh for the basic ORC-R134a and 0.0493 $/kWh for the regenerative ORC- R123, respectively. It is worth mentioning that the degree of superheat was the most influential variable in the optimization process.

Chagnon-Lessard et al. [100] numerically analyzed the performance of subcritical and transcritical ORC systems. The design variables which were operating parameters such as pressures and mass flow rates and the working fluid were optimized with the purpose of maximizing the power output. Through an approximate analysis, the authors of this study developed a novel relation for evaluating the maximum specific power output of an ORC unit.

The optimization procedure of a geothermal-fed ORC with the application of a coaxial heat exchanger was studied by Mokhtari et al.

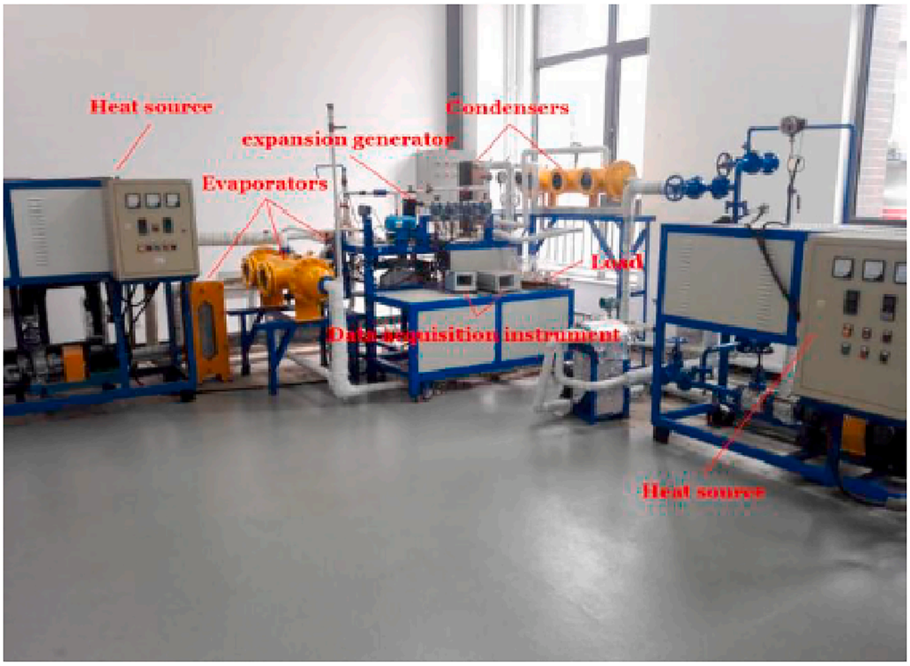


Fig. 30. A photograph of the examined experimental setup by Ref. [85]. (License Number: 5115150307900).

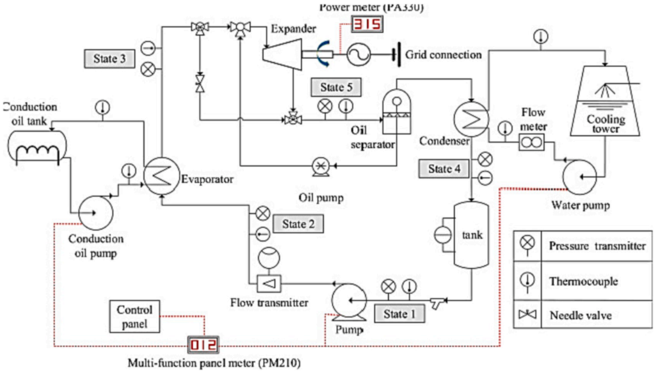


Fig. 31. Depiction of the investigated power generation unit by Ref. [86]. (License Number: 5115150496762).

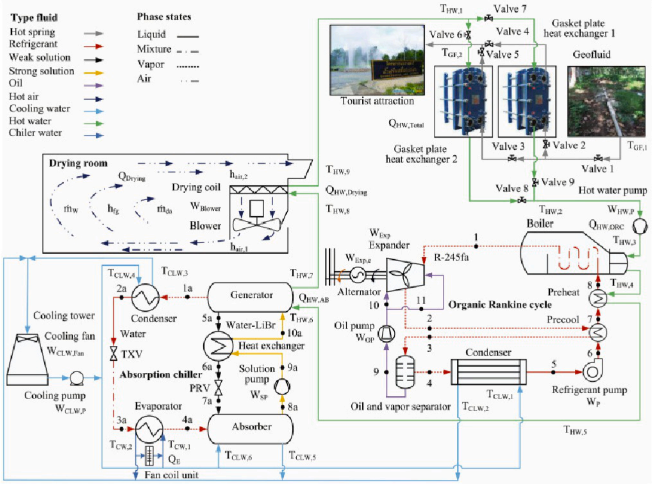


Fig. 32. A schematic view of the suggested power production system by Ref. [90]. (License Number: 5115150821017).

Table 3
Summary for experimental performance investigations of the geothermal-driven ORC system.

Study	Brief title	Highlights	Ref.
Tang et al. (2015)	Twin-screw expander in a geothermal ORC	Twin-screw expanders can be effectively coupled with heat sources over a wide range of temperatures.	[81]
Yang et al. (2017)	An ORC system using a geothermal resource from abandoned oil wells	According to the experimental test, the efficiency of the suggested turbine and ORC were 78.52 % and 5.33%.	[82]
Hu et al. (2017)	Design and test of a geothermal-driven ORC system in Huabei Oilfield, China	To have the stability of the system's operation, the stability of the geothermal water flow rate was essential.	[83]
Wang et al. (2017)	A variable-capacity power system driven by geothermal energy	The power generated by the flash-ORC system increased by decreasing the load.	[84]
Song et al. (2019)	Solar and geothermal energy coupled power generation system	The efficiency of the hybrid-driven ORC system was 11.21% higher than that of the single geothermal-driven ORC.	[85]
Lin et al. (2019)	The behavior of a 10 kW ORC using a scroll-type expander	Net thermal efficiency of 8.9% and net electricity efficiency of 7.9%.	[86]
Chao et al. (2019)	The stability study of a flash-binary power system	The optimum organic fluid mass flow rate was determined according to the different temperatures of the heat source.	[87]
Chaiyat et al. (2020)	Levelized energy and exergy costs per life cycle assessment of a co-generation system	The CCHP unit generated net output energy and exergy of 32.62 kWh and 6.98 kWh, respectively.	[88]
Welzl et al. (2020)	Experimental evaluation of nucleate pool boiling heat transfer correlations	A higher power output of the ORC unit was achieved with R245fa as the working fluid than with R1233zd(E).	[89]

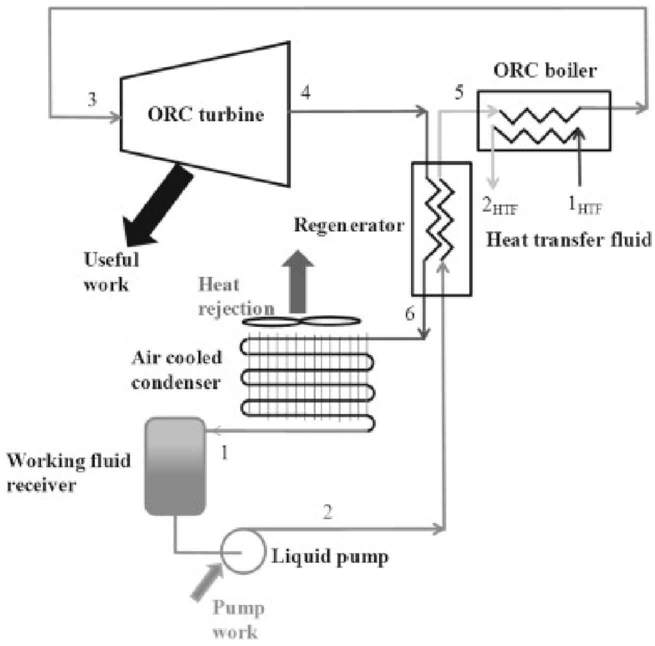


Fig. 33. Depiction of the evaluated ORC regenerative system by Ref. [94]. (License Number: 5115150990743).

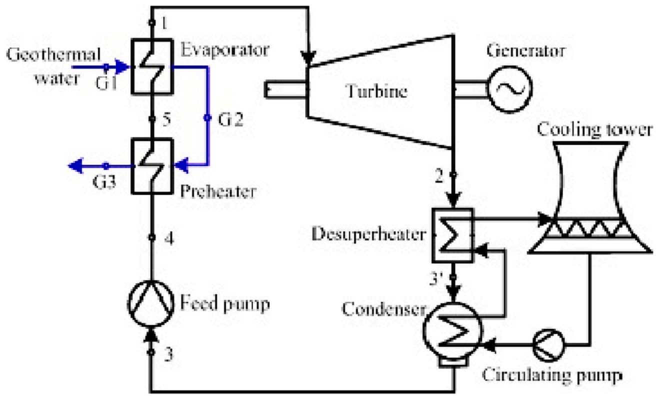


Fig. 34. A schematic view of the suggested system driven by geothermal water [96]. (License Number: 5115151123740).

[101]. Different working fluids were investigated including R123, R134a, R245fa, and R22. They reported that the exergy and energy efficiencies increased to 8.7% and 13% respectively when using the optimum configuration of the ORC. Zhao et al. [102] investigated a geothermal-driven system for electricity production and cooling as depicted in Fig. 37. An ORC system and an ejector refrigeration cycle were applied for power generation and cooling respectively. The suggested system was evaluated based on thermodynamic and exergo-economic investigations. The system was optimized for maximizing the exergetic efficiency and minimizing the levelized cost per unit exergy of products using two single-objective optimizations. It was reported that the best thermodynamic performance could not obtain the calculated optimal exergo-economic design.

Design and optimization for the structural and operational parameters of geothermal-driven ORC for power generation under different environmental conditions were carried out by Huster et al. [103]. They used isobutene as the organic fluid of the ORC. They found higher power generation at lower ambient temperatures, whereas they reported levelized costs of electricity of between 41 US-$/MWh and 60 US-$/MWh at an optimum design. Zhu et al. [104] investigated numerical modeling for presenting the optimum power generation map based on geothermal energy. The main goal was performance comparison of DF, FORC, and DFORC cycles with SF cycle for increasing power generation by 20% with R245fa as working fluid. For the best thermodynamic performance, the FORC and DF cycles were recommended for a geofluid temperature of less than 170 °C, and greater than 170 °C, respectively. Furthermore, Zhao et al. [105] and Lu et al. [106] considered the optimum flash and evaporation temperatures of the SF, DF, FORC and DFORC based on geothermal energy. The generation of maximum net power output was selected as an objective function during the optimization process. Five different organic fluids were investigated including R123, R152a, isobutane, n-pentane and R245fa. The investigated systems were considered based on techno-economic analyses. The SF system showed the lowest performance compared to the other investigated power generation systems. Zhou et al. [107] optimized a geothermal-driven ORC system as presented in Fig. 38. The particle swarm optimizer (PSO) was used for the optimization of the power output. The Sabalan geothermal power plant in Ardabil, Iran, was investigated as a case study for driving the ORC system. The energy and exergy efficiencies were calculated at 18.2% and 62.4% respectively. Also, they reported zeotropic mixtures for generating the highest power output.

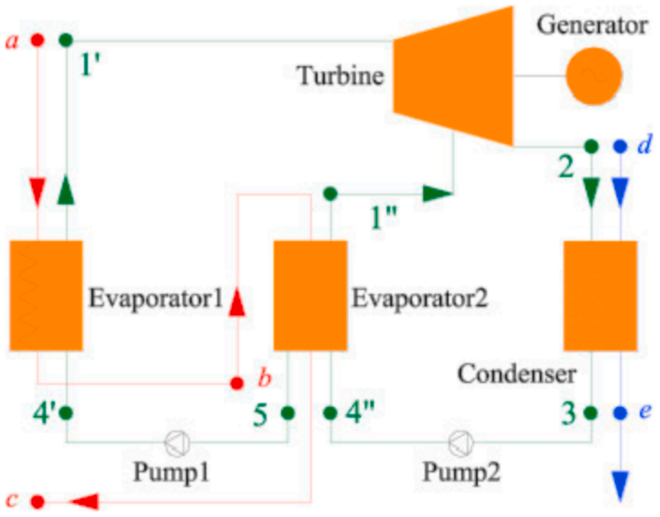


Fig. 35. Depiction of the investigated system by Ref. [97]. (License Number: 5115151263667).

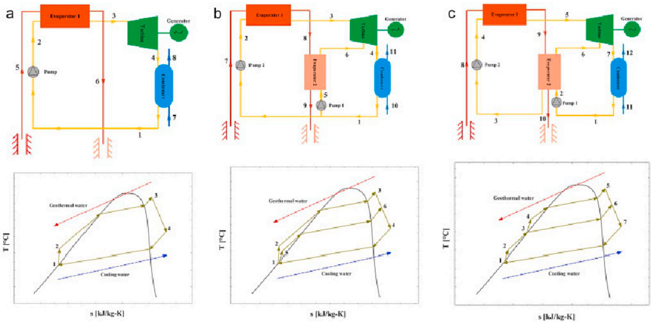


Fig. 36. Configurations and T-s diagrams of the three examined configurations of Ref. [98]. (License Number: 5115151425085).

One of the parameters impacting the thermodynamic and economic performance of a geothermal-driven ORC unit is the evaporator pinch point temperature difference (PPTD). In detail, lower evaporator PPTD increases the heat transfer area and the investment cost although yielding higher turbine work. Regarding this issue, Sun et al. [108] optimized the evaporation temperature of an ORC unit run by a

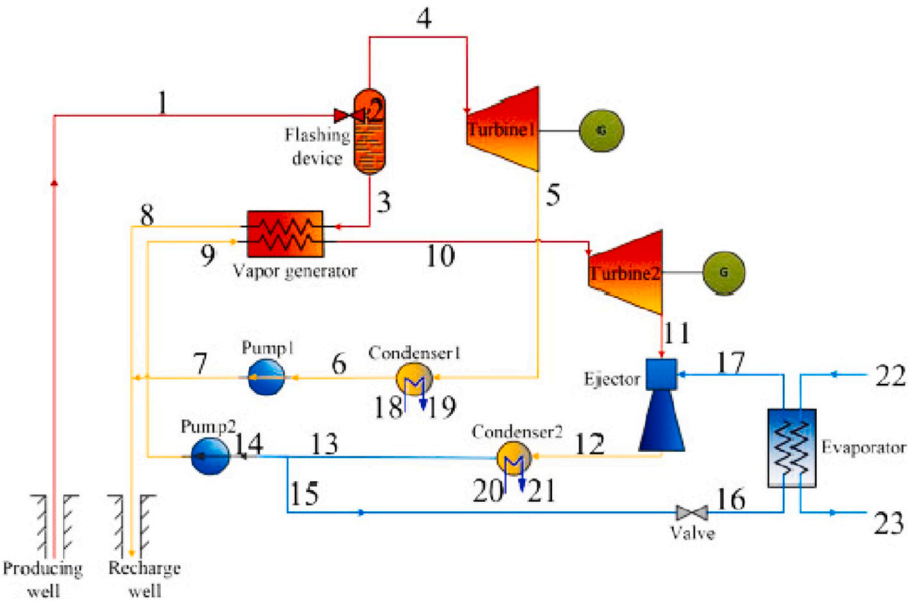


Fig. 37. A schematic view of a system with two turbines and ejectors driven by geothermal energy [102]. (License Number: 5115160043914).

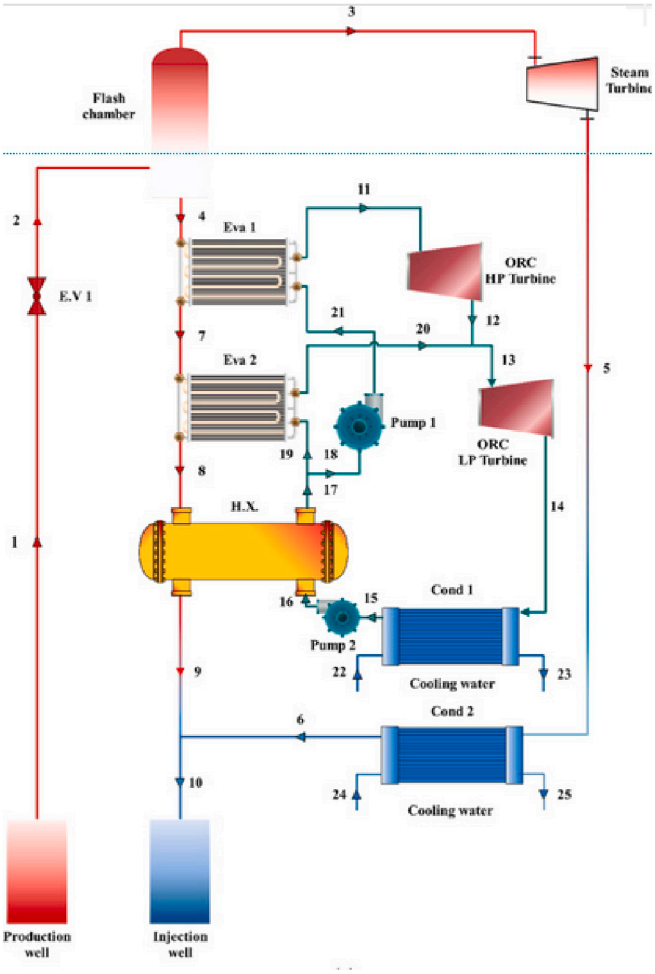


Fig. 38. A schematic diagram of a steam power cycle and an ORC fed by geothermal energy [107]. (License Number: 5115160220706).

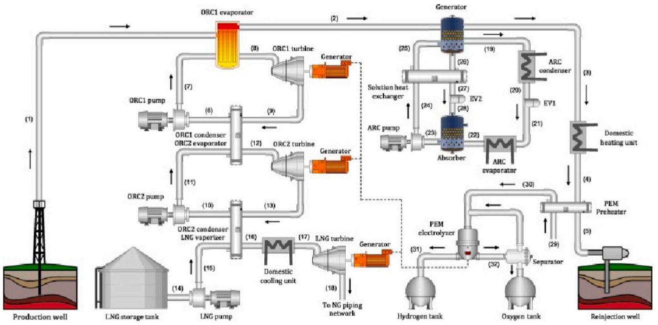


Fig. 39. Depiction of a system with double stage ORC and other devices driven by geothermal energy [113]. (License Number: 5115160355915).

geothermal resource to obtain the maximum power output on condition that the PPTDs and the brine inlet temperatures ranged 4–15 °C and 100–150 °C, respectively. The main result indicated that the ORC generated 1.7–2.6% more power output with every 1 °C fall in the PPTD of the evaporator when the brine inlet temperatures were greater than 130 °C. Similarly, Li et al. [109] analyzed the influence of PPTDs and heat source conditions on the thermo-economic operation of dual-pressure evaporation ORC when the heat source temperature varied between 100 and 200 °C and the mass flow rates were chosen as 5 kg/s, 10 kg/s, and 15 kg/s. The authors observed that the growth in the heat source temperature and mass flow rate decreased the specific investment cost; also an increase in the PPTDs enhanced the thermo-economic performance of the unit. With regards to this condition, a geothermal resource was introduced as an attractive source of energy to run an ORC.

In another similar study, the performance of single-pressure and dual-pressure evaporation ORCs were optimized and compared to each other. The heat source temperatures were considered between 100 °C and 200 °C. It was observed that the highest electrical output of the dual-pressure evaporation ORC was larger than that of the single-pressure evaporation ORC. Also, the efficiency of the system was highly dependent on the evaporation pressures and evaporator outlet temperatures on the condition that the condensation temperature of the cycle was constant [110].

Shokati et al. [111] assessed the performance of the basic, dual-pressure and dual-fluid ORCs and Kalina cycle run by a geothermal

Table 4
Summary of the optimization investigations of the geothermal-driven ORC system.

Study	Brief title	Highlights	Ref.
Hettiarachchi et al. (2007)	Optimum design criteria for a geothermal ORC	Parameters such as evaporation and condensation temperatures, geothermal and cooling water velocities were changed to acquire the optimal design.	[91]
Shengjun et al. (2011)	A subcritical ORC and transcritical power cycle system	R123 and R125 yielded the highest exergy efficiency and the most cost-effective system, respectively.	[92]
Manente et al. (2013)	An ORC design for the control strategy	The authors optimized the system according to the variation of environmental conditions.	[93]
Garg et al. (2013)	Isopentane, R-245fa and their mixtures as working fluids for ORC	The optimum energy efficiency was reported to be around 13% for the mixtures of working fluids.	[94]
Maraver et al. (2014)	Optimization of ORCs constrained by technical parameters	A guideline for optimizing the ORC system with regenerative and non-regenerative cycles was introduced.	[95]
Liu et al. (2015)	Geothermal ORCs using R600a/R601a mixtures	To generate the same power with a lower heat transfer area, the geothermal source temperature should rise.	[96]
Li et al. (2015)	Optimization of ORC using two-stage evaporation	TSORC performed better compared to ORC for power generation.	[97]
Shokati et al. (2015)	Optimization of basic, dual-pressure and dual-fluid ORCs and Kalina power plants	The dual-pressure ORC produced the highest amount of electrical power and the Kalina cycle generated electricity at the lowest unit cost of power.	[111]
Sadeghi et al. (2016)	Various ORC configurations using zeotropic mixtures	The usage of zeotropic mixtures increased the power generation of a simple ORC by 27.76%.	[98]
Mokhtari et al. (2016)	A geothermal Rankine cycle utilizing a coaxial heat exchanger	The optimum design of the ORC system increased the exergy and energy efficiencies to 8.7% and 13%.	[101]
Zhao et al. (2016)	Optimization of a CCP system driven by the geothermal source	The exergy efficiency and the average levelized costs were optimized by two single-objective optimization methods.	[102]
Chagnon-Lessard et al. (2016)	Geothermal power plants with the maximum specific power output	Based on an approximate analysis, a novel relation for predicting the maximum specific power output of an ORC unit was developed.	[100]
Huster et al. (2017)	Design of a geothermal ORC	Lower ambient temperatures were more suitable for a geothermal-driven ORC system.	[103]
Zhu et al. (2017)	Optimum flash and evaporation temperatures under different geofluid conditions	To improve the power generation unit by 20%, four different power generation cycles were studied.	[104]
Zhao et al. (2017)	Optimum flash and evaporation temperatures under different geofluid conditions	It was found that the optimum flash and evaporation temperatures rose with an increase in geofluid temperature and dryness.	[105]
Karimi and Mansouri (2017)	Optimization of different ORC configurations	The degree of superheat was known as the most influential parameter on the optimization process.	[99]
Lu et al. (2018)	Compound power cycles for enhanced geothermal systems	The five different systems including SF, DF, FORC and DFORC were compared to each other based on levelized electricity cost and payback period.	[106]
Sun et al. (2018)	Effects of evaporator PPTD on the performance of ORC	The ORC generated a 1.7–2.6% more power per 1 °C decrease in the PPTD of the evaporator.	[108]
Li et al. (2018)	Comparison of single-pressure and dual-pressure evaporation ORC	The highest electrical output of the dual-pressure evaporation ORC was larger than that of the single-pressure evaporation ORC.	[110]
Zhou et al. (2019)	Geothermal flash and dual-pressure evaporation ORC	Zeotropic mixtures yielding the maximum output power consisted of Pentane /Cis-2-butene, and Pentane/ Trans-2-butene.	[107]
Emadi and Mahmoudimehr (2019)	A geothermal heat source and LNG heat sink	The optimized unit produced power with a total cost rate of 424 $/hr and exergy efficiency of 24.92%.	[113]
Özkaraca and Keçebaş (2019)	Maximum exergy efficiency of a geothermal power plant	The unit was optimized by the gravitational search algorithm.	[114]
Li et al. (2019)	A novel ORC with supercritical-subcritical heat absorption process coupling	The novel ORC yielded far more efficient than the dual-pressure evaporation and the typical subcritical cycles	[112]
Li et al. (2020)	Evaluations of dual-pressure evaporation ORC	The increase in the heat source temperature and mass flow rate decreased the specific investment cost	[109]

fluid reservoir. First, they optimized the aforementioned cycles in a way that they yielded the maximum power output with the lowest unit cost of generated electricity. Then, they compared the outcomes of each unit. It was shown that the dual-pressure ORC produced the highest amount of electrical power and the Kalina cycle produced electricity at the lowest unit cost of power.

Li et al. [112] introduced a novel ORC unit in which both supercritical and subcritical heat absorption processes were coupled into a single cycle. It should be noted that in this study, the heat source temperature was between 130 °C and 200 °C which was similar to the temperature of the geothermal heat resource. It was expected that this new system complemented the merits of transcritical cycles and dual-pressure evaporation. To obtain the highest value of the net power, the effective parameters including the outlet temperature of the vapor

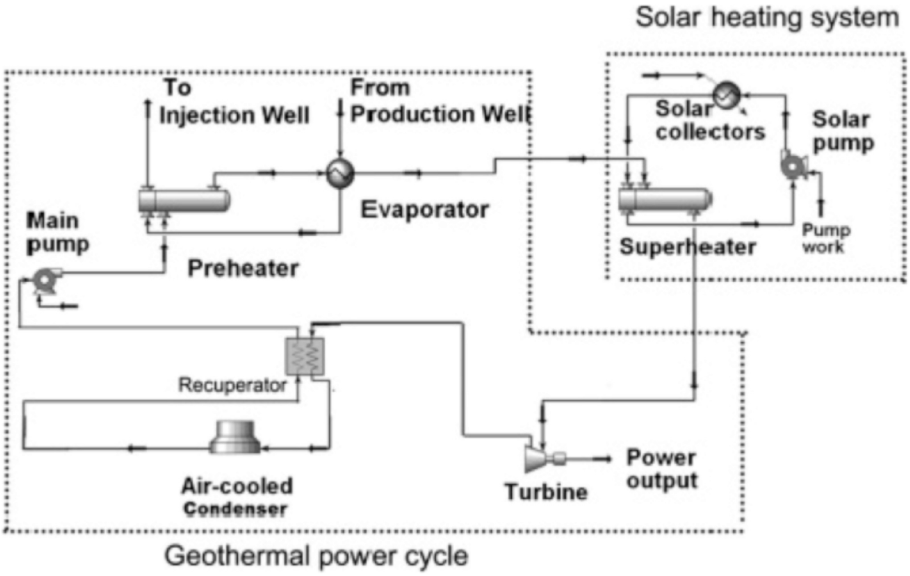


Fig. 40. Depiction of the suggested hybrid power generation system by Ref. [117] which exploits both solar and geothermal energy. (License Number: 5115160507991).

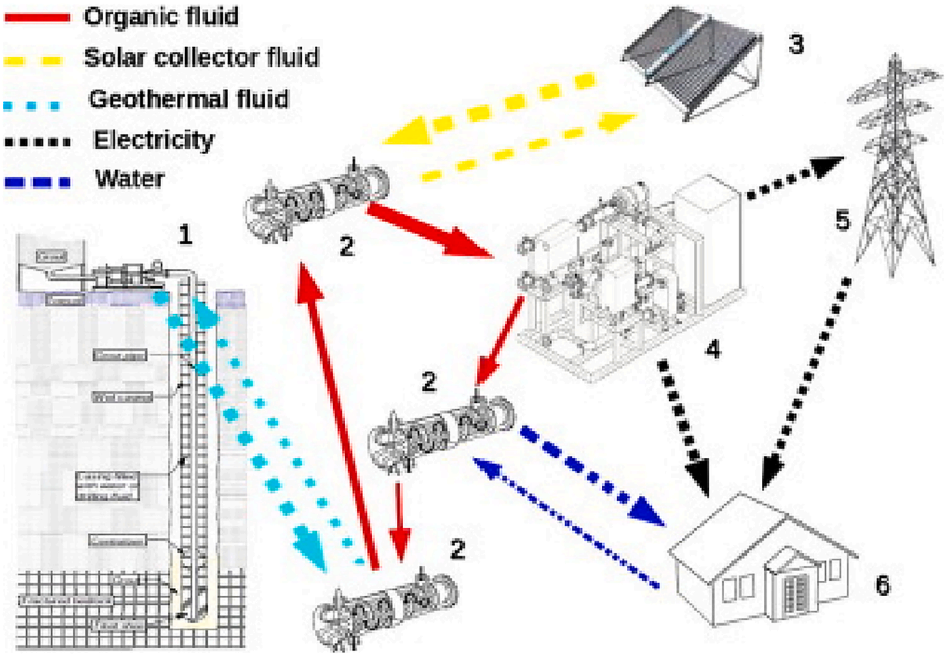


Fig. 41. Depiction of the suggested system by Ref. [114]. (License Number: 5115160783310).

generator and The heat absorption pressures were optimized. Final results indicated that the novel ORC yielded substantially more efficient in comparison with the dual-pressure evaporation and the typical subcritical cycles. Also, the heat absorption capacity increased by employing the novel unit compared to the transcritical cycle.

A polygeneration unit based on a geothermal working fluid as the heat source and an LNG re-gasification process as the heat sink was investigated by Emadi and Mahmoudimehr [113] thermodynamically and economically. Two ORC systems were placed between the heat source and the heat sink for power generation as shown in Fig. 39. They conducted a comprehensive parametric analysis and an optimization study based on the coupling Genetic Algorithm (Artificial Neural Network). The optimum design yielded a total cost rate of 424 $/hr, a hydrogen production capacity of 276.1 kg/hr, and exergy efficiency of 24.92%. Özkaraca and Keçebaş [114] numerically optimized the thermodynamic efficiency of a geothermal-driven ORC unit for power generation based on a gravitational search algorithm. The exergetic efficiency of the optimized ORC was 31%.

In conclusion, as also shown by Lee et al. [115] and Haghighi et al. [5], many research efforts have gone into modeling and optimization in order to improve geothermal-driven ORC systems. A recent study by Zhi et al. [116] can be highlighted, where a novel transcritical-subcritical ORC with zeotropic mixtures was optimized. They reported that, by adopting a zeotropic mixture, system performance can be significantly enhanced.

A summary of optimization works for geothermal-driven ORC systems is presented in Table 4. There are different optimization methods that have been found in the literature like the steepest descent method

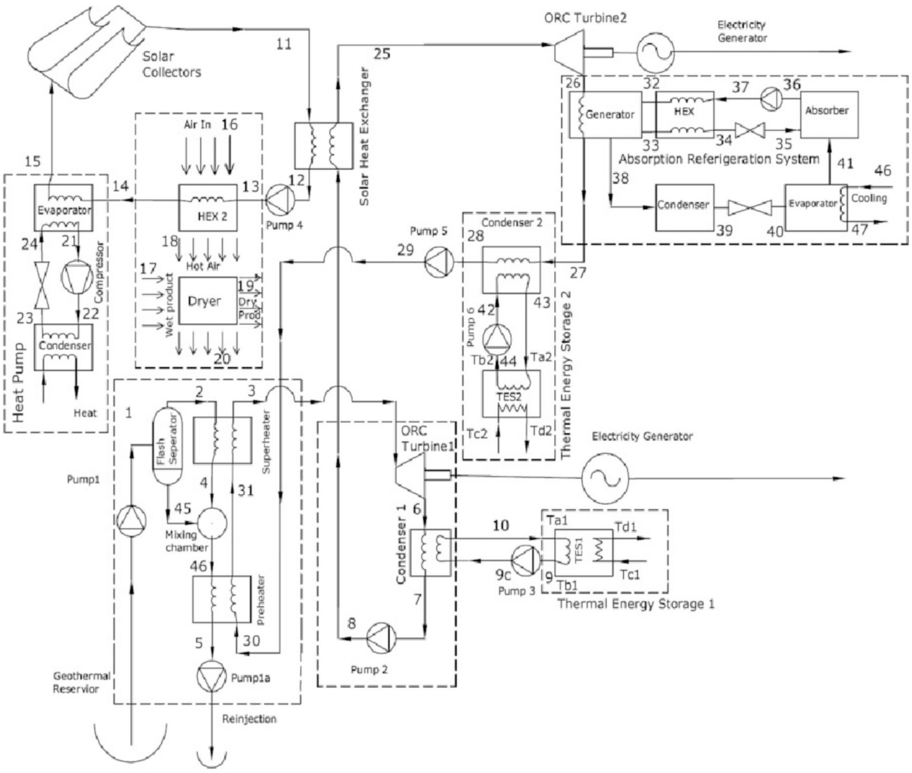


Fig. 42. Depiction of a complex polygeneration system that exploits solar and geothermal energy [119]. (License Number: 5115160968034).

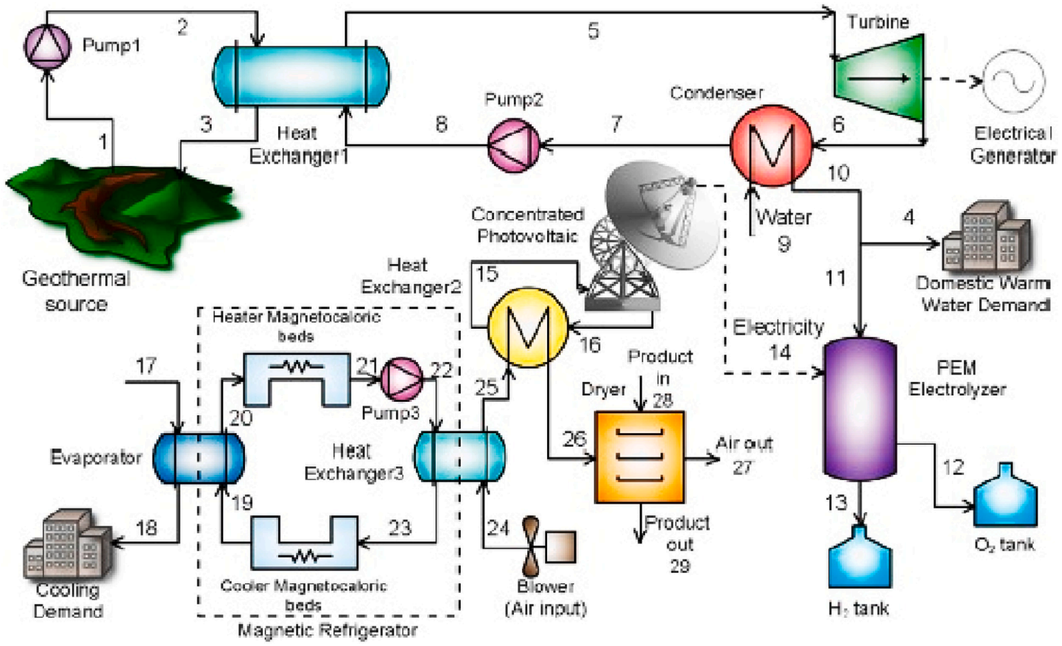


Fig. 43. A Depiction of o a polygeneration system driven by geothermal energy and solar concentrating photovoltaics [120]. (License Number: 5115161100171).

and the use of Genetic Algorithms. Usually, the optimization variables are temperature levels, pressure levels and pinch point temperature differences. The use of optimization is able to increase the system performance by about 20%-30% which is an important enhancement.

6. Hybrid solar/geothermal ORC systems

Hybrid systems are introduced for increasing the performance of geothermal-driven ORC systems. Usually, geothermal energy is combined with solar irradiation to enhance the energy input potential in the system and to exploit two renewable energy sources. Zhou [117] investigated a hybrid geothermal/solar-driven ORC system for power generation based on subcritical and supercritical power cycles as depicted in Fig. 40. They reported that the suggested hybrid power configuration could generate 19% more electricity annually as compared with the two stand-alone power plants. Ruzzenenti et al.

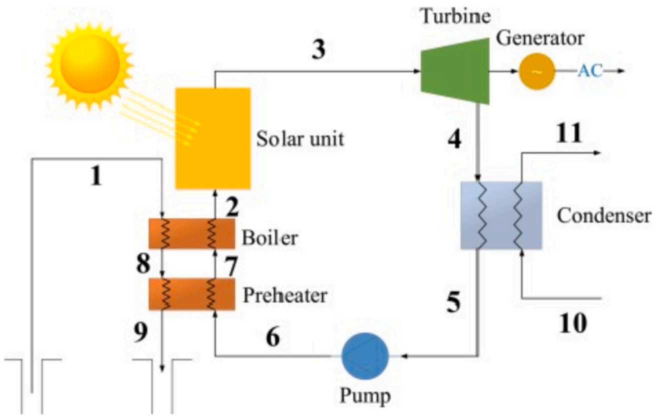


Fig. 44. Depiction of an ORC which is driven by solar and geothermal energy [122]. (License Number: 5115161257344).

[118] investigated a combined geothermal-solar system coupled with an organic Rankine cycle for the producing of heat and power based on environmental sustainability aspects as shown in Fig. 41. They evaluated the feasibility of exploiting abandoned wells.

Islam and Dincer [119] studied a combined solar-geothermal system as a polygeneration system as exhibited in Fig. 42. The system was investigated based on energy and exergy investigations for 4 cases including single-generation, co-generation, tri-generation and polygeneration. The influence of many parameters on energy and exergy performance was considered. They found the energy and exergy efficiencies of the polygeneration unit to be 51% and 62% respectively. Boyaghchi and Nazer [120] suggested a polygeneration system for generating power, producing hydrogen and oxygen, cooling, heating, and drying. Combined geothermal energy and concentrated photovoltaic thermal were coupled to the system as depicted in Fig. 43. They found that the cost reduced by 18.3% and the environmental impact criteria improved by 24.9% when the system was optimized. Energy efficiency increased by about 27.4% and the exergy efficiency improved about 2 times. Furthermore, they reported that the power generation improved by 50.3% as compared to the nominal point.

A model was presented by Li et al. [121] for performance optimization of a hybrid geothermal/solar-driven ORC by applying a compound objective function methodology. They concluded that the performance of the ORC system increased when coupling with hybrid geothermal/solar energy compared to using a single heat source. Khosravi et al. [122] developed an artificial intelligence approach for modeling a hybrid geothermal/solar-driven ORC unit for electricity production as displayed in Fig. 44. The method for this modeling was conducted by the ANFIS optimized with PSO (ANFIS-PSO) and MLP-PSO. The modeling was developed based on thermodynamic and financial aspects of the ORC technology. Different design parameters were considered during modeling including solar irradiation, well temperature level, working fluid flow rate, turbine outlet pressure level, collecting area and inlet pressure level in the preheater. They reported better modeling results of the hybrid ORC system with ANFIS-PSO than with MLP-PSO. Atiz et al. [123] numerically considered a hybrid geothermal/solar-driven ORC system for power generation under energy, exergy, and power output aspects as presented in Fig. 45. They found that the application of the solar collector had an effective influence on enhancing the performance of the suggested ORC system. The highest energy and exergy efficiency values of the unit were reported as 6.92% and 21.06% using n-butane as the ORC fluid respectively.

A new hybrid geothermal-solar ORC system with flash-binary configuration was suggested by Wan et al. [124] as displayed in Fig. 46. The energy and exergy efficiency values o were reported at 10.74% and 23.9% respectively. They found that the thermodynamic performance improves with increasing flash pressure. Hybrid geothermal/solar-driven ORC systems have been investigated by many researchers as an effective approach for improving power generation performance [125,126]. Liu et al. [127] presented a hybrid geothermal/fossil energy-driven ORC unit for power generation. Geothermal energy was used for preheating the feedwater in the coal-fired power system. They developed models for the investigation of two configurations including parallel and serial geothermal preheating configurations. They studied the impact of different geothermal temperatures on performance. They concluded that the serial configuration generally generated more power than the parallel configuration. Lastly, Heidarnejad et al. [128] presented a thermodynamic study of a biomass-geothermal power plant combined with a desalination system. It was reported that energetic and exergetic efficiencies of 13.9% and 19.4% could be reached respectively. Further information in relation to the biodiesel fuel properties and applications can be found in Refs [129–134].

A summary of the related works to the performance investigations of

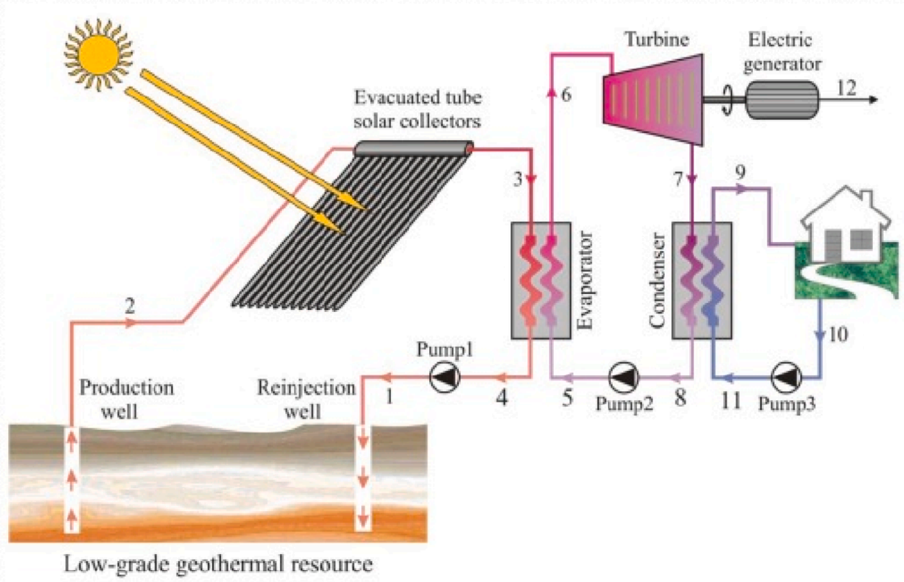


Fig. 45. Depiction of a power system with evacuated tube solar collectors and geothermal reservoir [123]. (License Number: 5115161395955).

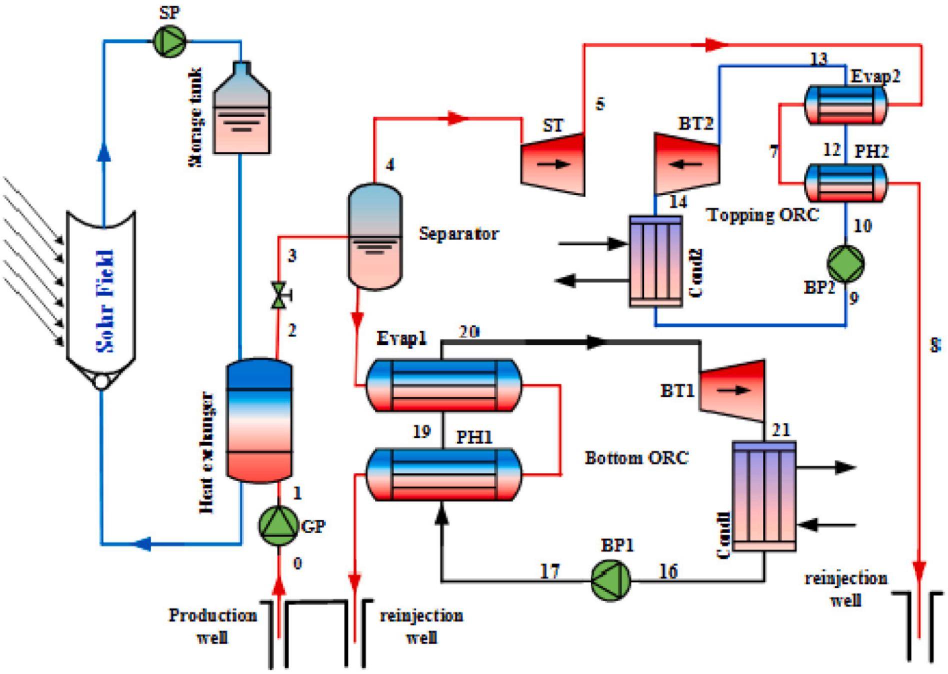


Fig. 46. A schematic view of a power system with parabolic trough solar collectors and geothermal reservoir [124]. (License Number: 5115161499838).

hybrid solar/geothermal ORC is reported in Table 5. It is worthy to state that the use of hybrid systems leads to higher energy and exergy efficiency values compared to the geothermal-only configurations. The most usual choice is to combine solar and geothermal energy sources. There are different options for solar technology like parabolic trough solar collectors, evacuated tube collectors, or concentrating thermal photovoltaics.

7. Challenges and opportunities

Geothermal energy is a renewable and sustainable energy source and thus it is an attractive choice that concentrates a great amount of interest. The relatively low-temperature levels of this energy source make it ideal for coupling with the ORC. Generally, ORC exhibits a better performance as compared with the Kalina cycle when coupled with the geothermal energy sources [25,29]. On the other hand, natural refrigerants, such as R600a, are promising choices for the ORC from both the environmental and the energy points of view [31]. From the energetic perspective R245fa and R141b appear to be good choices, however, they are not environmentally friendly and thus they should not be preferred.

The parallel configuration is more efficient than the series one in power and heat production systems [36,37,40]. An enhancement as high as 51% has been reported with the parallel configuration [40]. The literature search revealed that the highest performance is obtained in the multigeneration system [45] with 64.2% energetic efficiency and 50.9% exergetic efficiency. Moreover, the exergy efficiency of a geothermal-based ORC with supercritical CO_2 is found to be around 45% [47]. On the other hand, the experimental studies indicate relatively lower efficiency values [82,86]. Thus, more experimental studies are needed to validate the above-mentioned high-performance results in relation to the geothermal-based ORC systems.

An increase in the geothermal temperature level enhances significantly the unit performance. The increase of the geothermal temperature from 130 °C to 200 °C led to a 150% increase in hydrogen production [51], while the temperature increases from 110 °C to 150 °C led to a 300% increase in electricity production of the ORC [54]. Using the optimization techniques, further performance improvement in the range of 20% to 30% has been achieved [98,104].

The levelized cost of electricity with a geothermal ORC system is found to be as low as 0.0831 $/kWh in [78] with a payback period of about 9 years. Some other studies claim much lower payback periods with geothermal ORC systems, e.g. as low as 2.7 years [68] and around 2 years with a geothermal-natural gas system [74]. These results are encouraging for the viability of the geothermal-driven ORC systems.

Geothermal energy is an important energy source; however, it faces some serious limitations. More specifically, geothermal power plants require a high amount of investment due to the high drilling cost. Moreover, the extraction of geothermal energy is associated with the release of greenhouse gases and this fact leads to possible environmental limitations. The release of gases like CO_2, NH_3 and H_2S from the geothermal power generation systems has to be taken into serious consideration for the environmental assessment and in the life cycle analysis.

Another issue that may lead to limitations in geothermal applications, especially in urban areas, is the need for extensive land utilization to obtain high amounts of heat inputs. The use of vertical ground heat exchangers is a solution to this problem. On the other hand, the geothermal heat sink may possibly lead to cooling down the ground gradually. In such a case, the system has to shut down its operation for some period of time and then restart when the ground reaches the proper temperature levels.

The ORC systems, especially the ones with low capacity come at a relatively high cost. Moreover, the working fluids are flammable and toxic in some cases. Thus, there is a need for a suitable selection of the working fluids. When compared with the water/steam cycles, the ORC systems provide restricted performance due to the low and medium operating temperature levels. Therefore, their careful design is needed in order to enhance the thermodynamic efficiency of the ORC devices and especially the expander.

8. Future directions

A significant amount of work is available in the literature on the domain of geothermal-based ORC units. However, more research efforts are needed in order to improve the efficiency of these units and eliminate the limitations mentioned above. It is important to optimize these systems using novel algorithms which use artificial intelligence in order

Table 5
Summary for the performance investigations of hybrid solar/geothermal ORC systems.

Study	Brief title	Highlights	Ref.
Zhou (2014)	Hybridization of solar and geothermal energy	The supercritical hybrid unit generated electrical power more economically than stand-alone systems.	[117]
Ruzzenenti et al. (2014)	A micro-CHP system fueled by geothermal and solar energy	The feasibility of exploiting abandoned wells was investigated in this research.	[118]
Liu et al. (2016)	A hybrid geothermal–fossil power generation system	The role of geothermal energy was the preheating of the feed water in the coal-fired power unit.	[22]
Islam and Dincer (2017)	A solar and geothermal energy-based integrated system	Four kinds of systems, single generation, cogeneration, tri-generation, and multi-generation, were investigated regarding exergy and energy efficiency.	[119]
Ahmadi Boyaghchi and Nazer (2017)	Concentrated photovoltaic thermal-geothermal system	An 18.3% reduction in cost and a 24.9% improvement in environmental impact criteria were attained by optimizing the proposed unit.	[120]
Li et al. (2018)	TSORC is driven by geothermal energy coupled with solar energy	The hybrid unit performed more efficiently compared to the system with a single heat source.	[121]
Khosravi et al. (2019)	A geothermal based-ORC equipped with a solar system	The effect of parameters including solar radiation, well temperature, and surface area of the solar collector on the performance of the hybrid unit was investigated.	[122]
Atiz et al. (2019)	A low-temperature geothermal resource and solar energy	The maximum overall energy and exergy efficiencies were 6.92% and 21.06% respectively when n-butane was the ORC working fluid.	[123]
Wan et al. (2019)	A geothermal-solar flash-binary hybrid system	Energy and exergy efficiencies were evaluated as 10.74% and 23.9%, respectively.	[124]

to minimize the computational time during the optimization procedure. In any case, energy, exergy and financial aspects have to be taken into account during the optimization procedures.

Moreover, there is a need for investigating new organic fluids which are ideal for the operating temperature levels of the geothermal-driven units. Natural refrigerants are promising and the binary mixtures have to be tested theoretically and experimentally. Fluids with low global warming potential and zero ozone depletion potential are ideal choices, as well as they have to be safe choices (low flammability and low toxicity). Moreover, the cost of organic fluids has to be reasonable to reduce the overall cost of the systems.

There is a need for conducting experimental studies with different scales. More specifically, investigation of higher capacity systems is needed in order to predict the efficiency of commercial size systems accurately. The computationally optimized models need to be validated through the experimental results in order to have multilateral approximations.

More studies should be conducted to study the simultaneous use of geothermal energy and other heat sources. A combination of geothermal energy and waste heat may be considered in this regard. Finally, the use of geothermal energy in polygeneration systems is another issue worth investigating in order to analyze various heat inputs in highly efficient systems with many useful outputs. The exploitation of the geothermal potential in the building sector through the use of polygeneration units is an important area to be investigated more in the future.

9. Conclusions

Organic Rankine cycles can convert low-grade heat input into work with an acceptable conversion ratio. Geothermal energy is one of the most promising renewable energies that can provide heat input at different temperature levels. The goal of the present review paper is to investigate the different aspects of the geothermal-driven ORC in order to define the cases with the highest performance and the most important parameters that affect the system efficiency. The emphasis in determining the performance is given to the energy efficiency, exergy efficiency, financial indexes, environmental parameters, optimization procedures and experimental studies. Hybrid solar/geothermal ORC systems including geothermal units with different solar collectors were also reviewed. The following conclusions can be derived from the current work:

- Geothermal-driven ORC systems lead to viable investments with relatively low payback periods.
- There are cases with high energy and exergy efficiencies, especially in the cases with more useful outputs (e.g. multigeneration systems). This indicates the need for combining geothermal energy and ORC with additional energy devices.
- The parallel configuration is more efficient than the series configuration in electrical and heat production.
- Natural working fluids are promising choices for achieving high efficiency and environmentally friendly systems. The toxicity and flammability issues need to be taken into account for choosing the proper working mediums.
- The optimization of the system is able to increase the performance by around 20% to 30% that is important in order to have sustainable configurations.
- Especially in polygeneration systems with geothermal energy, there is a possibility to achieve high efficiency. So, the system energy efficiency of 65% and exergy efficiency of 50% can be achieved.
- The exploitation of geothermal energy as the heat source in power systems is a financially promising choice that can lead to a low payback period which is ranges from 2 up to 9 years.
- The increase of the geothermal temperature levels leads to higher exergy input and the possibility for increasing the electricity production (or the other useful products) at a higher level. However, it has to be commented that the higher geothermal temperature leads to higher drilling costs and also increases the difficulty of extracting heat.
- There is a need for further practical and experimental studies about the combination of ORC with geothermal plants especially in hybrid systems with geothermal energy and solar or waste heat inputs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Marefati, M. Mehrpooya, S.A. Mousavi, Introducing an integrated SOFC, linear Fresnel solar field, Stirling engine and steam turbine combined cooling, heating and power process, Int. J. Hydrogen Energy 44 (2019) 30256–30279.

[2] M.H. Jahangir, S.A. Mousavi, M.A.V. Rad, A techno-economic comparison of a photovoltaic/thermal organic Rankine cycle with several renewable hybrid systems for a residential area in Rayen, Iran, Energy Convers. Manage. 195 (2019) 244–261.

[3] M. Mehrpooya, S.A. Mousavi, Advanced exergoeconomic assessment of a solar-driven Kalina cycle, Energy Convers. Manage. 178 (2018) 78–91.

[4] Q. Liu, Y. Duan, Z. Yang, Performance analyses of geothermal organic Rankine cycles with selected hydrocarbon working fluids, Energy 63 (2013) 123–132.

[5] A. Haghighi, M.R. Pakatchian, M.E.H. Assad, V.N. Duy, M. Alhuyi Nazari, A review on geothermal Organic Rankine cycles: modeling and optimization, J. Therm. Anal. Calorim. 144 (5) (2021) 1799–1814, https://doi.org/10.1007/s10973-020-10357-y.

[6] B.I. Ismail, Renewable Geothermal Energy Explorations, (2019).

[7] S.-M. Lu, A global review of enhanced geothermal system (EGS), Renew. Sustain. Energy Rev. 81 (2018) 2902–2921.

[8] A. Paulillo, L. Cotton, R. Law, A. Striolo, P. Lettieri, Geothermal energy in the UK: The life-cycle environmental impacts of electricity production from the United Downs Deep Geothermal Power project, J. Cleaner Prod. 249 (2020), 119410.

[9] J.W. Tester, B.J. Anderson, A. Batchelor, D. Blackwell, R. DiPippo, E. Drake, J. Garnish, B. Livesay, M. Moore, K. Nichols, The future of geothermal energy, Massachusetts Inst. Technol. 358 (2006).

[10] S.J. Zarrouk, H. Moon, Efficiency of geothermal power plants: A worldwide review, Geothermics 51 (2014) 142–153.

[11] C. Vetter, H.-J. Wiemer, D. Kuhn, Comparison of sub-and supercritical Organic Rankine Cycles for power generation from low-temperature/low-enthalpy geothermal wells, considering specific net power output and efficiency, Appl. Therm. Eng. 51 (2013) 871–879.

[12] J. Song, C.-W. Gu, Parametric analysis of a dual loop Organic Rankine Cycle (ORC) system for engine waste heat recovery, Energy Convers. Manage. 105 (2015) 995–1005.

[13] M. Astolfi, M.C. Romano, P. Bombarda, E. Macchi, Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium–low temperature geothermal sources–Part B: Techno-economic optimization, Energy 66 (2014) 435–446.

[14] W.-L. Cheng, T.-T. Li, Y.-L. Nian, K. Xie, Evaluation of working fluids for geothermal power generation from abandoned oil wells, Appl. Energy 118 (2014) 238–245.

[15] F. Heberle, D. Brüggemann, Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation, Appl. Therm. Eng. 30 (2010) 1326–1332.

[16] X. Wang, E.K. Levy, C. Pan, C.E. Romero, A. Banerjee, C. Rubio-Maya, L. Pan, Working fluid selection for organic Rankine cycle power generation using hot produced supercritical CO2 from a geothermal reservoir, Appl. Therm. Eng. 149 (2019) 1287–1304.

[17] G. Györke, U.K. Deiters, A. Groniewsky, I. Lassu, A.R. Imre, Novel classification of pure working fluids for Organic Rankine Cycle, Energy 145 (2018) 288–300.

[18] A. Groniewsky, G. Györke, A.R. Imre, Description of wet-to-dry transition in model ORC working fluids, Appl. Therm. Eng. 125 (2017) 963–971.

[19] A. Modi, F. Haglind, A review of recent research on the use of zeotropic mixtures in power generation systems, Energy Conversión and Management 138 (2017) 603–626.

[20] F. Heberle, C. Schifflechner, D. Brüggemann, Life cycle assessment of Organic Rankine Cycles for geothermal power generation considering low-GWP working fluids, Geothermics 64 (2016) 392–400.

[21] A.I. Papadopoulos, M. Stijepovic, P. Linke, P. Seferlis, S. Voutetakis, Multi-level design and selection of optimum working fluids and ORC systems for power and heat cogeneration from low enthalpy renewable sources, Comput. Aided Chem. Eng., Elsevier (2012) 66–70.

[22] W. Liu, D. Meinel, C. Wieland, H. Spliethoff, Investigation of hydrofluoroolefins as potential working fluids in organic Rankine cycle for geothermal power generation, Energy 67 (2014) 106–116.

[23] D.H. Brownell, S.K. Garg, J.W. Pritchett, Governing equations for geothermal reservoirs, Water Resour. Res. 13 (6) (1977) 929–934.

[24] G. Paloso, B. Mohanty, Cascading vapour absorption cycle with organic rankine cycle for enhancing geothermal power generation, Renewable Energy 3 (6-7) (1993) 669–681.

[25] Z. Guzović, D. Lončar, N. Ferdelji, Possibilities of electricity generation in the Republic of Croatia by means of geothermal energy, Energy 35 (8) (2010) 3429–3440.

[26] E. Sauret, A.S. Rowlands, Candidate radial-inflow turbines and high-density working fluids for geothermal power systems, Energy 36 (2011) 4460–4467.

[27] A. Franco, Power production from a moderate temperature geothermal resource with regenerative Organic Rankine Cycles, Energy Sustain Dev 15 (2011) 411–419.

[28] N. Kazemi, F. Samadi, Thermodynamic, economic and thermo-economic optimization of a new proposed organic Rankine cycle for energy production from geothermal resources, Energy Convers. Manage. 121 (2016) 391–401.

[29] Z. Guzović, B. Majcen, S. Cvetković, Possibilities of electricity generation in the Republic of Croatia from medium-temperature geothermal sources, Appl. Energy 98 (2012) 404–414.

[30] R. Gabbrielli, A novel design approach for small scale low enthalpy binary geothermal power plants, Energy Convers. Manage. 64 (2012) 263–272.

[31] T. Li, J. Zhu, W. Zhang, Cascade utilization of low temperature geothermal water in oilfield combined power generation, gathering heat tracing and oil recovery, Appl. Therm. Eng. 40 (2012) 27–35.

[32] F.-Z. Zhang, P.-X. Jiang, Thermodynamic analysis of a binary power cycle for different EGS geofluid temperatures, Appl. Therm. Eng. 48 (2012) 476–485.

[33] W. Fu, J. Zhu, T. Li, W. Zhang, J. Li, Comparison of a Kalina cycle based cascade utilization system with an existing organic Rankine cycle based geothermal power system in an oilfield, Appl. Therm. Eng. 58 (2013) 224–233.

[34] A.R. Mohan, U. Turaga, V. Shembekar, D. Elsworth, S.V. Pisupati, Utilization of carbon dioxide from coal-based power plants as a heat transfer fluid for electricity generation in enhanced geothermal systems (EGS), Energy 57 (2013) 505–512.

[35] A.A. AlZaharani, I. Dincer, G. Naterer, Performance evaluation of a geothermal based integrated system for power, hydrogen and heat generation, Int. J. Hydrogen Energy 38 (2013) 14505–14511.

[36] M. Habka, S. Ajib, Determination and evaluation of the operation characteristics for two configurations of combined heat and power systems depending on the heating plant parameters in low-temperature geothermal applications, Energy Convers. Manage. 76 (2013) 996–1008.

[37] T. Li, J. Zhu, W. Zhang, Comparative analysis of series and parallel geothermal systems combined power, heat and oil recovery in oilfield, Appl. Therm. Eng. 50 (2013) 1132–1141.

[38] M. Habka, S. Ajib, Studying effect of heating plant parameters on performances of a geothermal-fuelled series cogeneration plant based on Organic Rankine Cycle, Energy Convers. Manage. 78 (2014) 324–337.

[39] J. Hsieh, Y. Lee, T. Guo, L. Liu, P. Cheng, C. Wang, A co-axial multi-tube heat exchanger applicable for a geothermal ORC power plant, Energy Procedia 61 (2014) 874–877.

[40] D. Fiaschi, A. Lifshitz, G. Manfrida, D. Tempesti, An innovative ORC power plant layout for heat and power generation from medium-to low-temperature geothermal resources, Energy Convers. Manage. 88 (2014) 883–893.

[41] M. Habka, S. Ajib, Evaluation of mixtures performances in Organic Rankine Cycle when utilizing the geothermal water with and without cogeneration, Appl. Energy 154 (2015) 567–576.

[42] F. Heberle, M. Preißinger, D. Brüggemann, Zeotropic mixtures as working fluids in Organic Rankine Cycles for low-enthalpy geothermal resources, Renewable Energy 37 (2012) 364–370.

[43] Q. Liu, Y. Duan, Z. Yang, Effect of condensation temperature glide on the performance of organic Rankine cycles with zeotropic mixture working fluids, Appl. Energy 115 (2014) 394–404.

[44] A.R. Mohan, U. Turaga, V. Subbaraman, V. Shembekar, D. Elsworth, S.V. Pisupati, Modeling the CO2-based enhanced geothermal system (EGS) paired with integrated gasification combined cycle (IGCC) for symbiotic integration of carbon dioxide sequestration with geothermal heat utilization, Int. J. Greenhouse Gas Control 32 (2015) 197–212.

[45] M. Malik, I. Dincer, M.A. Rosen, Development and analysis of a new renewable energy-based multi-generation system, Energy 79 (2015) 90–99.

[46] M.J. Proctor, W. Yu, R.D. Kirkpatrick, B.R. Young, Dynamic modelling and validation of a commercial scale geothermal organic rankine cycle power plant, Geothermics 61 (2016) 63–74.

[47] G. Manente, L. Da Lio, A. Lazzaretto, Influence of axial turbine efficiency maps on the performance of subcritical and supercritical Organic Rankine Cycle systems, Energy 107 (2016) 761–772.

[48] V. Zare, A comparative thermodynamic analysis of two tri-generation systems utilizing low-grade geothermal energy, Energy Convers. Manage. 118 (2016) 264–274.

[49] Q. An, Y. Wang, J. Zhao, C. Luo, Y. Wang, Direct utilization status and power generation potential of low-medium temperature hydrothermal geothermal resources in Tianjin, China: a review, Geothermics 64 (2016) 426–438.

[50] Y. Sun, J. Lu, J. Wang, T. Li, Y. Li, Y. Hou, J. Zhu, Performance improvement of two-stage serial organic Rankine cycle (TSORC) integrated with absorption refrigeration (AR) for geothermal power generation, Geothermics 69 (2017) 110–118.

[51] Y.E. Yuksel, M. Ozturk, Thermodynamic and thermoeconomic analyses of a geothermal energy based integrated system for hydrogen production, Int. J. Hydrogen Energy 42 (2017) 2530–2546.

[52] S. Van Erdeweghe, J. Van Bael, B. Laenen, W. D'haeseleer,, Comparison of series/parallel configuration for a low-T geothermal CHP plant, coupled to thermal networks, Renewable Energy 111 (2017) 494–505.

[53] M.S. Sadaghiani, M. Ahmadi, M. Mehrpooya, F. Pourfayaz, M. Feidt, Process development and thermodynamic analysis of a novel power generation plant driven by geothermal energy with liquefied natural gas as its heat sink, Appl. Therm. Eng. 133 (2018) 645–658.

[54] T. Li, Y. Xu, J. Wang, X. Kong, J. Zhu, Polygeneration energy system driven by associated geothermal water for oilfield in high water cut stage: A theoretical study, Geothermics 76 (2018) 242–252.

[55] Y.-L. Nian, W.-L. Cheng, Insights into geothermal utilization of abandoned oil and gas wells, Renew. Sustain. Energy Rev. 87 (2018) 44–60.

[56] E. Akrami, I. Khazaee, A. Gholami, Comprehensive analysis of a multi-generation energy system by using an energy-exergy methodology for hot water, cooling, power and hydrogen production, Appl. Therm. Eng. 129 (2018) 995–1001.

[57] W.R. Huster, A.M. Schweidtmann, A. Mitsos, Impact of accurate working fluid properties on the globally optimal design of an organic Rankine cycle, in, Computer Aided Chemical Engineering, Elsevier (2019) 427–432.

[58] H. Karakilcik, M. Erden, M. Karakilcik, Investigation of hydrogen production performance of chlor-alkali cell integrated into a power generation system based on geothermal resources, Int. J. Hydrogen Energy 44 (2019) 14145–14150.

[59] M. Ebadollahi, H. Rostamzadeh, M.Z. Pedram, H. Ghaebi, M. Amidpour, Proposal and assessment of a new geothermal-based multigeneration system for cooling, heating, power, and hydrogen production, using LNG cold energy recovery, Renewable Energy 135 (2019) 66–87.
[60] M. Aneke, B. Agnew, C. Underwood, Performance analysis of the Chena binary geothermal power plant, Appl. Therm. Eng. 31 (2011) 1825–1832.
[61] T. Li, J. Zhu, S. Xin, W. Zhang, A novel geothermal system combined power generation, gathering heat tracing, heating/domestic hot water and oil recovery in an oilfield, Geothermics 51 (2014) 388–396.
[62] L.Y. Bronicki, Electrical power from moderated temperature geothermal sources with modular mini-power plants, Geothermics 17 (1988) 83–92.
[63] B. Vonsée, W. Crijns-Graus, W. Liu, Energy technology dependence-A value chain analysis of geothermal power in the EU, Energy 178 (2019) 419–435.
[64] D. Bonalumi, P. Bombarda, C. Invernizzi, Potential performance of environmental friendly application of ORC and Flash technology in geothermal power plants, Energy Procedia 129 (2017) 621–628.
[65] B. Mohanty, G. Paloso Jr, Economic power generation from low-temperature geothermal resources using organic Rankine cycle combined with vapour absorption chiller, Heat Recovery Syst. CHP 12 (1992) 143–158.
[66] T. Guo, H. Wang, S. Zhang, Fluids and parameters optimization for a novel cogeneration system driven by low-temperature geothermal sources, Energy 36 (2011) 2639–2649.
[67] F. Vélez, J.J. Segovia, M.C. Martín, G. Antolín, F. Chejne, A. Quijano, A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation, Renew. Sustain. Energy Rev. 16 (2012) 4175–4189.
[68] M. Eyidogan, F.C. Kilic, D. Kaya, V. Coban, S. Cagman, Investigation of Organic Rankine Cycle (ORC) technologies in Turkey from the technical and economic point of view, Renew. Sustain. Energy Rev. 58 (2016) 885–895.
[69] J.M. Rodríguez, D. Sánchez, G.S. Martínez, B. Ikken, Techno-economic assessment of thermal energy storage solutions for a 1 MWe CSP-ORC power plant, Sol. Energy 140 (2016) 206–218.
[70] D. Fiaschi, G. Manfrida, E. Rogai, L. Talluri, Exergoeconomic analysis and comparison between ORC and Kalina cycles to exploit low and medium-high temperature heat from two different geothermal sites, Energy Convers. Manage. 154 (2017) 503–516.
[71] E. Akrami, A. Chitsaz, H. Nami, S. Mahmoudi, Energetic and exergoeconomic assessment of a multi-generation energy system based on indirect use of geothermal energy, Energy 124 (2017) 625–639.
[72] R.S. El-Emam, I. Dincer, Exergy and exergoeconomic analyses and optimization of geothermal organic Rankine cycle, Appl. Therm. Eng. 59 (2013) 435–444.
[73] A. Aali, N. Pourmahmoud, V. Zare, Exergoeconomic analysis and multi-objective optimization of a novel combined flash-binary cycle for Sabalan geothermal power plant in Iran, Energy Convers. Manage. 143 (2017) 377–390.
[74] S. Yao, Y. Zhang, X. Yu, Thermo-economic analysis of a novel power generation system integrating a natural gas expansion plant with a geothermal ORC in Tianjin, China, Energy 164 (2018) 602–614.
[75] P. Behnam, A. Arefi, M.B. Shafii, Exergetic and thermoeconomic analysis of a trigeneration system producing electricity, hot water, and fresh water driven by low-temperature geothermal sources, Energy Convers. Manage. 157 (2018) 266–276.
[76] M. Kahraman, A.B. Olcay, E. Sorgüven, Thermodynamic and thermoeconomic analysis of a 21 MW binary type air-cooled geothermal power plant and determination of the effect of ambient temperature variation on the plant performance, Energy Convers. Manage. 192 (2019) 308–320.
[77] S. Di Fraia, A. Macaluso, N. Massarotti, L. Vanoli, Energy, exergy and economic analysis of a novel geothermal energy system for wastewater and sludge treatment, Energy Convers. Manage. 195 (2019) 533–547.
[78] N. Meng, T. Li, Y. Jia, H. Qin, Q. Liu, W. Zhao, G. Lei, Techno-economic performance comparison of enhanced geothermal system with typical cycle configurations for combined heating and power, Energy Convers. Manage. 205 (2020), 112409.
[79] M. Tartiere, Astolfi, A world overview of the Organic Rankine Cycle market, Energy Procedia 129 (2017) 2–9.
[80] T. Li, Q. Liu, Y. Xu, Z. Dong, N. Meng, Y. Jia, H. Qin, Techno-economic performance of multi-generation energy system driven by associated mixture of oil and geothermal water for oilfield in high water cut, Geothermics 89 (2021), 101991.
[81] H. Tang, H. Wu, X. Wang, Z. Xing, Performance study of a twin-screw expander used in a geothermal organic Rankine cycle power generator, Energy 90 (2015) 631–642.
[82] Y. Yang, Y. Huo, W. Xia, X. Wang, P. Zhao, Y. Dai, Construction and preliminary test of a geothermal ORC system using geothermal resource from abandoned oil wells in the Huabei oilfield of China, Energy 140 (2017) 633–645.
[83] K. Hu, J. Zhu, W. Zhang, X. Lu, A case study of an ORC geothermal power demonstration system under partial load conditions in Huabei Oilfield, China, Energy Procedia 142 (2017) 1327–1332.
[84] Y. Wang, G. Chen, J. Wang, C. Luo, Q. An, J. Zhao, A variable-capacity power system driven by geothermal energy: research methodology and preliminary experimental study, Energy Procedia 142 (2017) 278–283.
[85] A. Song, J. Zhu, P. Zhang, N. Chang, Z. Cui, Experimental Research on Solar and Geothermal Energy Coupling Power Generation System, Energy Procedia 158 (2019) 5982–5987.
[86] C.-H. Lin, P.-P. Hsu, Y.-L. He, Y. Shuai, T.-C. Hung, Y.-Q. Feng, Y.-H. Chang, Investigations on experimental performance and system behavior of 10 kW organic Rankine cycle using scroll-type expander for low-grade heat source, Energy 177 (2019) 94–105.
[87] L. Chao, G. Yulie, L. Zhenneng, Z. Jun, W. Yongzhen, The Stability Study of Flash-Binary Power System Based on Experiment, Energy Procedia 158 (2019) 6055–6060.
[88] N. Chaiyat, S. Chaongew, P. Ondokmai, P. Makarkard, Levelized energy and exergy costings per life cycle assessment of a combined cooling, heating, power and tourism system of the San Kamphaeng hot spring, Thailand, Renewable Energy 146 (2020) 828–842.
[89] M. Welzl, F. Heberle, D. Brüggemann, Experimental evaluation of nucleate pool boiling heat transfer correlations for R245fa and R1233zd (E) in ORC applications, Renewable Energy 147 (2020) 2855–2864.
[90] J. Wang, X. Zhang, Y. Zhang, X. Zhang, W. Wang, Experimental study of single screw expander used in low-medium temperature geothermal power system, Energy Procedia 61 (2014) 854–857.
[91] H.M. Hettiarachchi, M. Golubovic, W.M. Worek, Y. Ikegami, Optimum design criteria for an organic Rankine cycle using low-temperature geothermal heat sources, Energy 32 (2007) 1698–1706.
[92] Z. Shengjun, W. Huaixin, G. Tao, Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation, Appl. Energy 88 (2011) 2740–2754.
[93] G. Manente, A. Toffolo, A. Lazzaretto, M. Paci, An Organic Rankine Cycle off-design model for the search of the optimal control strategy, Energy 58 (2013) 97–106.
[94] P. Garg, P. Kumar, K. Srinivasan, P. Dutta, Evaluation of isopentane, R-245fa and their mixtures as working fluids for organic Rankine cycles, Appl. Therm. Eng. 51 (2013) 292–300.
[95] D. Maraver, J. Royo, V. Lemort, S. Quoilin, Systematic optimization of subcritical and transcritical organic Rankine cycles (ORCs) constrained by technical parameters in multiple applications, Appl. Energy 117 (2014) 11–29.
[96] Q. Liu, A. Shen, Y. Duan, Parametric optimization and performance analyses of geothermal organic Rankine cycles using R600a/R601a mixtures as working fluids, Appl. Energy 148 (2015) 410–420.
[97] T. Li, Q. Wang, J. Zhu, K. Hu, W. Fu, Thermodynamic optimization of organic Rankine cycle using two-stage evaporation, Renewable Energy 75 (2015) 654–664.
[98] M. Sadeghi, A. Nemati, M. Yari, Thermodynamic analysis and multi-objective optimization of various ORC (organic Rankine cycle) configurations using zeotropic mixtures, Energy 109 (2016) 791–802.
[99] S. Karimi, S. Mansouri, A comparative profitability study of geothermal electricity production in developed and developing countries: Exergoeconomic analysis and optimization of different ORC configurations, Renewable Energy 115 (2018) 600–619.
[100] N. Chagnon-Lessard, F. Mathieu-Potvin, L. Gosselin, Geothermal power plants with maximized specific power output: Optimal working fluid and operating conditions of subcritical and transcritical Organic Rankine Cycles, Geothermics 64 (2016) 111–124.
[101] H. Mokhtari, H. Hadiannasab, M. Mostafavi, A. Ahmadibeni, B. Shahriari, Determination of optimum geothermal Rankine cycle parameters utilizing coaxial heat exchanger, Energy 102 (2016) 260–275.
[102] Y. Zhao, J. Wang, L. Cao, Y. Wang, Comprehensive analysis and parametric optimization of a CCP (Combined cooling and power) system driven by geothermal source, Energy 97 (2016) 470–487.
[103] W.R. Huster, D. Bongartz, A. Mitsos, Deterministic global optimization of the design of a geothermal organic rankine cycle, Energy Procedia 129 (2017) 50–57.
[104] J. Zhu, K. Hu, W. Zhang, X. Lu, A study on generating a map for selection of optimum power generation cycles used for Enhanced Geothermal Systems, Energy 133 (2017) 502–512.
[105] Y. Zhao, X. Lu, J. Zhu, W. Zhang, K. Hu, G. Xin, F. Jiang, Z. Qin, A study on selecting optimum flash and evaporation temperatures for four geothermal power generation systems under different geofluid's conditions, Energy Procedia 142 (2017) 439–446.
[106] X. Lu, Y. Zhao, J. Zhu, W. Zhang, Optimization and applicability of compound power cycles for enhanced geothermal systems, Appl. Energy 229 (2018) 128–141.
[107] Y. Zhou, S. Li, L. Sun, S. Zhao, S.S. Ashraf Talesh, Optimization and thermodynamic performance analysis of a power generation system based on geothermal flash and dual-pressure evaporation organic Rankine cycles using zeotropic mixtures, Energy 194 (2020) 116785, https://doi.org/10.1016/j.energy.2019.116785.
[108] J. Sun, Q. Liu, Y. Duan, Effects of evaporator pinch point temperature difference on thermoeconomic performance of geothermal organic Rankine cycle systems, Geothermics 75 (2018) 249–258.
[109] J. Li, Z. Yang, S. Hu, F. Yang, Y. Duan, Thermo-economic analyses and evaluations of small-scale dualpressure evaporation organic Rankine cycle system using pure fluids, Energy 206 (2020), 118217.
[110] J. Li, Z. Ge, Y. Duan, Z. Yang, Q. Liu, Parametric optimization and thermodynamic performance comparison of single-pressure and dual-pressure evaporation organic Rankine cycles, Appl. Energy 217 (2018) 409–421.
[111] N. Shokati, F. Ranjbar, M. Yari, Exergoeconomic analysis and optimization of basic, dual-pressure and dual-fluid ORCs and Kalina geothermal power plants: A comparative study, Renewable Energy 83 (2015) 527–542.
[112] J. Li, Z. Ge, Y. Duan, Z. Yang, Design and performance analyses for a novel organic Rankine cycle with supercritical-subcritical heat absorption process coupling, Appl. Energy 235 (2019) 1400–1414.

[113] M.A. Emadi, J. Mahmoudimehr, Modeling and thermo-economic optimization of a new multi-generation system with geothermal heat source and LNG heat sink, Energy Convers. Manage. 189 (2019) 153–166.

[114] O. Özkaraca, A. Keçebaş, Performance analysis and optimization for maximum exergy efficiency of a geothermal power plant using gravitational search algorithm, Energy Convers. Manage. 185 (2019) 155–168.

[115] I. Lee, J.W. Tester, F. You, Systems analysis, design, and optimization of geothermal energy systems for power production and polygeneration: State-of-the-art and future challenges, Renew. Sustain. Energy Rev. 109 (2019) 551–577.

[116] L. Zhi, P. Hu, L. Chen, G. Zhao, Performance analysis and optimization of engine waste heat recovery with an improved transcritical-subcritical parallel organic Rankine cycle based on zeotropic mixtures, Appl. Therm. Eng. 181 (2020), 115991.

[117] C. Zhou, Hybridisation of solar and geothermal energy in both subcritical and supercritical Organic Rankine Cycles, Energy Convers. Manage. 81 (2014) 72–82.

[118] F. Ruzzenenti, M. Bravi, D. Tempesti, E. Salvatici, G. Manfrida, R. Basosi, Evaluation of the environmental sustainability of a micro CHP system fueled by low-temperature geothermal and solar energy, Energy Convers. Manage. 78 (2014) 611–616.

[119] S. Islam, I. Dincer, Development, analysis and performance assessment of a combined solar and geothermal energy-based integrated system for multigeneration, Sol. Energy 147 (2017) 328–343.

[120] F.A. Boyaghchi, S. Nazer, Assessment and optimization of a new sextuple energy system incorporated with concentrated photovoltaic thermal-Geothermal using exergy, economic and environmental concepts, J. Cleaner Prod. 164 (2017) 70–84.

[121] T. Li, X. Hu, J. Wang, X. Kong, J. Liu, J. Zhu, Performance improvement of two-stage serial organic Rankine cycle (TSORC) driven by dual-level heat sources of geothermal energy coupled with solar energy, Geothermics 76 (2018) 261–270.

[122] A. Khosravi, S. Syri, X. Zhao, M. Assad, An artificial intelligence approach for thermodynamic modeling of geothermal based-organic Rankine cycle equipped with solar system, Geothermics 80 (2019) 138–154.

[123] A. Atiz, H. Karakilcik, M. Erden, M. Karakilcik, Investigation energy, exergy and electricity production performance of an integrated system based on a low-temperature geothermal resource and solar energy, Energy Convers. Manage. 195 (2019) 798–809.

[124] P. Wan, L. Gong, Z. Bai, Thermodynamic analysis of a geothermal-solar flash-binary hybrid power generation system, Energy Procedia 158 (2019) 3–8.

[125] H. Ghasemi, E. Sheu, A. Tizzanini, M. Paci, A. Mitsos, Hybrid solar–geothermal power generation: Optimal retrofitting, Appl. Energy 131 (2014) 158–170.

[126] F. Suleman, I. Dincer, M. Agelin-Chaab, Development of an integrated renewable energy system for multigeneration, Energy 78 (2014) 196–204.

[127] Q. Liu, L. Shang, Y. Duan, Performance analyses of a hybrid geothermal–fossil power generation system using low-enthalpy geothermal resources, Appl. Energy 162 (2016) 149–162.

[128] P. Heidarnejad, H. Genceli, M. Asker, S. Khanmohammadi, A comprehensive approach for optimizing a biomass assisted geothermal power plant with freshwater production: Techno-economic and environmental evaluation, Energy Convers. Manage. 226 (2020), 113514.

[129] G. Najafi, B. Ghobadian, T.F. Yusaf, H. Rahimi, Combustion analysis of a CI engine performance using waste cooking biodiesel fuel with an artificial neural network aid, Am. J. Appl. Sci. 4 (10) (2007) 759–767.

[130] G. Najafi, B. Ghobadian, LLK1694-wind energy resources and development in Iran, Renew. Sustain. Energy Rev. 15 (6) (2011) 2719–2728.

[131] T. Yusaf, I. Hamawand, P. Baker, G. Najafi, The effect of methanol-diesel blended ratio on ci engine performance, Int. J. Automot. Mech. Eng. 8 (2013) 1385–1395.

[132] E. Ettefaghi, B. Ghobadian, A. Rashidi, G. Najafi, M.H. Khoshtaghaza, M. Rashtchi, S. Sadeghian, A novel bio-nano emulsion fuel based on biodegradable nanoparticles to improve diesel engines performance and reduce exhaust emissions, Renewable Energy 125 (2018) 64–72.

[133] M.K. Abdolbaqi, W.H. Azmi, R. Mamat, N.M.Z.N. Mohamed, G. Najafi, Experimental investigation of turbulent heat transfer by counter and co-swirling flow in a flat tube fitted with twin twisted tapes, Int. Commun. Heat Mass Transfer 75 (2016) 295–302.

[134] O.M. Ali, R. Mamat, G. Najafi, T. Yusaf, S.M.S. Ardebili, Optimization of biodiesel-diesel blended fuel properties and engine performance with ether additive using statistical analysis and response surface methods, Energies 8 (12) (2015) 14136–14150.