Prospects of using organic Rankine cycle for geothermal power generation

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Article Info

Article history:

Received May 3, 2024
Revised Nov 11, 2024
Accepted Dec 26, 2024

Keywords:

Exergoeconomic analysis
Low-temperature sources
Return coefficient
System efficiency
Technical recommendations

ABSTRACT

The relevance of this study stems from the desire to develop efficient and sustainable methods of energy extraction from low-temperature geothermal resources, which is of key importance in the context of finding alternative energy sources and reducing dependence on conventional, often non-renewable sources. The purpose of this study was to analyze the organic Rankine cycle (ORC) to improve the efficiency of energy recovery from low-temperature geothermal sources. The present study employed the analytical method, the deduction method, the induction method, the functional method, the classification method, the synthesis method. ORC applications for geothermal energy were comprehensively analyzed, with a focus on the investigation of low-temperature resources. The best cycle performance parameters were determined, considering diverse operating conditions. Concrete technical recommendations were developed for the selection of organic working media to improve system efficiency. The summarized findings highlight the potential of the ORC in enhancing the sustainability and efficiency of geothermal systems.

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1. INTRODUCTION

Exploring the application of organic Rankine cycle (ORC) for geothermal energy with a focus on low-temperature resources is a critical and promising area of current research. With the growing interest in renewable energy sources and decreasing dependence on conventional sources, the study of best ORC operation parameters and the development of technical recommendations become of key importance. The problematic of the study lies in the technical and energy challenges associated with the use of ORC for geothermal energy. The issues of optimization of cycle operation parameters, selection of best organic working media and improvement of overall system efficiency are relevant and require in-depth analysis. Addressing these issues is essential to develop sustainable and efficient methods of extracting energy from low-temperature geothermal sources.

According to Bakyt *et al.* [1], a detailed analysis of ORC efficiency in low-temperature geothermal resources emphasizes the need to consider geothermal conditions when developing technical solutions. The study points out that the selection of best working media plays a crucial role in improving the efficiency of the system. However, it does not consider the impact of changing climatic conditions on ORC performance, leaving some aspects of adaptation to climate change out of consideration. Petuchov *et al*. [2] emphasize the significance of developing monitoring and maintenance systems, warning about possible technical difficulties and emphasizing the need for constant monitoring and maintenance of the system. Sungatova *et al*. [3] addressed not only the technical aspects but also the impact of ORC on the environmental sustainability of geothermal systems. This study emphasizes the importance of developing integrated approaches to incorporate environmental factors into system sustainability assessment. Viloria *et al*. [4] note the social and cultural aspects of ORC implementation, emphasizing that successful adaptation of the technology requires consideration of specific local socio-cultural features and community involvement in the development process.

Desai *et al*. [5] conducted a comparative analysis of two-phase expansion and subcritical ORC systems, focusing on their performance in solar and geothermal applications. They discovered that two-phase expansion systems might increase the efficiency of ORC systems by enhancing heat transmission, particularly in low-temperature settings. Cao *et al*. [6] developed a revolutionary integrated energy cascade system that combines liquid air energy storage and two-stage ORC cycles. Their findings showed that this integrated strategy greatly enhances thermodynamic performance, notably in terms of energy efficiency and storage capacity. Desai *et al*. and Cao *et al*. did not investigate the use of exergy and cost analysis to improve the performance of ORC systems in geothermal applications. However, one of the primary goals of this research is to get a more thorough understanding of the elements impacting ORC performance, which will lead to the development of more optimized and cost-effective ORC systems for geothermal energy generation. Alimgazin *et al*. [7] emphasize the significance of innovation in the creation of new materials required to improve ORC resistance at low temperatures, which could have a substantial impact on their large-scale implementation. This study does not explore in depth the impact of ORC on local economies and social structures, leaving the socio-economic aspects of the adoption of this technology without adequate attention. Mukhanov and Iskakova [8] put forward the issue of ORC adaptation to changing climatic conditions, which emphasizes the relevance of technological sustainability in the context of global climate change.

Previous research has mostly examined thermodynamic performance and applicability in solar, geothermal, and cryogenic energy storage situations. This study stresses enhancing the performance features of ORC by using organic working bodies, improving adaptability to varied geothermal environments, and boosting sustainability. It stresses ORC's practical use in remote areas, its promise for a cleaner energy future, and its environmental sustainability, particularly its low noise and vibration benefits. The research's relevance is illustrated by demonstrating ORC's environmental benefits, such as reduced noise and vibration, which make it appropriate for ecologically sensitive places. Furthermore, its scalability and adaptability are highlighted, demonstrating how ORC may be used in a variety of settings, leading to a more sustainable energy future.

2. MATERIALS AND METHODS

The analytical method helped to identify the key factors, to determine the interrelationships between them, and to cover complex phenomena in great detail, which allowed pinpointing the influence of various variables on the process under study. By using a statistical package for the social sciences (SPSS), regression analyses were performed to quantify the influence of these variables on system performance. Data points outside the normal operating range were excluded to ensure the accuracy and relevance of the results. To compare the performance of different working fluids, an analysis of variance (ANOVA) was conducted. The fluids analyzed included R245fa, pentane, and butane, and the analysis revealed statistically significant differences in system efficiency depending on the working fluid used ($p<0.05$). Data inclusion and exclusion decisions were made based on operational ranges and consistency among the obtained datasets. Data was only included if it met the predicted operational ranges for geothermal temperature (±2 °C) and system performance. Outliers were identified using Z-scores in SPSS, and those higher than ±3 were eliminated from the study. Additionally, data from instances in which technical issues such as malfunctions in equipment were reported were excluded to prevent distorting the results.

The analogy method was used to compare the utilization of ORC in geothermal systems to similar energy conversion technologies, such as steam turbines in solar thermal plants. This enabled the researchers to identify good practices and modify tactics that had previously proven beneficial in comparable low-temperature settings. The functional method was used to analyze the core functions and interrelationships within an ORC system, focusing on heat transfer, working fluid performance, and turbine mechanical output. This involved examination of the ORC system's primary components, such as the evaporator, condenser, and turbine, and assessing how each functioned under varying geothermal temperature conditions. The deductive method was utilized to organize prior knowledge of geothermal energy systems and ORC technology, allowing for the development of logical conclusions. Using this strategy, the researchers discovered cause-and-effect relationships between system design decisions (such as working fluid selection) and overall efficiency outcomes. Based on existing literature and data, the study concluded that some working fluids, such as R245fa, performed well in low-temperature geothermal environments due to their high thermal stability and minimal environmental effect. The method of synthesis helped to create a systematized and holistic image of a process or system by identifying the interrelationships and interactions between its components.

The inductive method was used to extract broad patterns from individual data points collected throughout the studies. This approach allowed the researchers to propose that organic working fluids with lower boiling points, such as pentane, are more successful in areas where geothermal resource temperatures are less than 100 °C. By applying this generalization method, it became possible to identify common features and characteristics in the area under consideration, which contributed to the formation of abstract models and concepts. The classification approach was utilized for categorizing the working fluids according to their thermodynamic properties, such as boiling points, critical temperatures, and environmental effects. The categorization also included the many types of geothermal resources studied, such as low- and medium-temperature sources. By aggregating the variables, the study was able to identify common traits across the various systems and expedite the process of optimizing the ORC for varied geothermal conditions.

The study employed ANOVA to examine the performance of several working fluids, including R245fa, pentane, and butane, under differing geothermal settings, demonstrating substantial changes in system efficiency. The functional technique investigated how these fluids interacted with essential system components such as the evaporator and turbine. By categorizing working fluids systematically based on thermodynamic parameters and geothermal resource types, the study produced a more precise and data-driven knowledge of how to design ORC systems for various geothermal situations.

3. RESULTS

Organic Rankine cycle (ORC) is an innovative thermal cycle that has become a subject of increasing interest in the energy sector. It provides an efficient mechanism for converting thermal energy into mechanical work using organic working media. One of the most promising applications of ORC is its use in geothermal energy. Geothermal energy is a renewable source and ORC provides an efficient means of extracting and utilizing it [9]. ORC's advantages in geothermal energy lie in its ability to deal with low-temperature geothermal resources that conventional methods may consider less efficient. This opens new prospects for utilizing geothermal energy in regions where high-temperature resources are limited. An essential aspect of ORC application in geothermal power generation is the ability to optimize the cycle performance parameters depending on the concrete operating conditions (Figure 1). Pilot tests have shown improved ORC performance compared to conventional geothermal energy extraction methods. This confirms the potential of ORC in improving the sustainability and efficiency of geothermal systems [10].

ORC stands out among thermal cycles as a powerful tool in converting thermal energy into mechanical work, especially in the context of low-temperature geothermal resources [12]. This approach effectively addresses the problems associated with conventional steam turbines, which are often inefficient when using low-temperature sources such as those with temperatures less than 100 ºC. Organic working bodies used in ORC have unique properties that allow efficient utilization of thermal energy at low temperatures [13]. This is especially significant when dealing with geothermal resources where high-temperature sources may be limited or unavailable. Applying ORC to low-temperature geothermal resources not only increases the availability of renewable energy but also expands the geographical scope within which geothermal sources can be utilized [14].

One of the features of ORC that gives it outstanding performance is its ability to adapt to variable temperature conditions. While conventional steam turbines can face challenges when dealing with geothermal sources where temperatures are not constant, ORC can efficiently utilize variable temperature resources. Geothermal sources such as hot springs, groundwater, or variable temperature geothermal springs are of particular interest to ORC [15]. ORC can provide stable and efficient power generation even under fluctuating temperature conditions. In the context of changing climatic conditions and the drive to increase the share of renewables in the energy matrix, ORC's performance at variable temperatures makes it a critical element in providing a stable energy source.

One of the principal advantages of ORCs in the context of geothermal energy is their ability to operate with low noise and vibration [16]. This feature makes ORCs more suitable for environmentally sensitive areas where environmental impact is critical. Conventional steam cycles are often accompanied by considerable levels of noise and vibration, which can have adverse consequences for the environment and animals. Organic cycles, on the other hand, provide a quiet and stable way to convert geothermal energy into electricity. This property is particularly valuable for nature reserves, national parks, and other sensitive ecosystems where it is critical to minimize human impact. ORCs can promote the sustainable use of geothermal resources in these areas without putting unnecessary stress on nature. Apart from low noise, less vibration is also a key advantage of ORC.

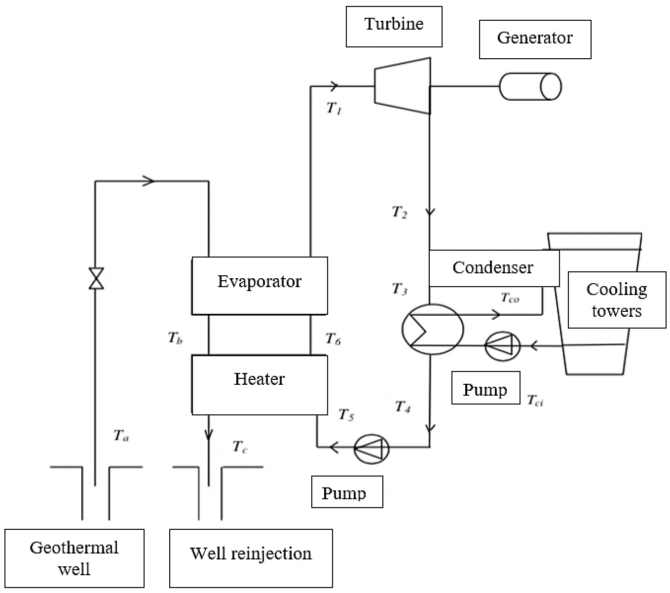

Figure 1. Configuration of geothermal power plant with binary cycle
Source: compiled by the authors based on [11]

Among the advantages of ORCs in the field of geothermal energy are their outstanding scalability and ability to integrate into modular systems [17]. This property gives this technology the flexibility needed to efficiently utilize geothermal sources of varying capacities. ORCs are easily scalable depending on need, making them an ideal choice for geothermal sources with varying characteristics. The efficiency of ORC is not lost with scale, which opens the door for the technology to be applied in a wide variety of scenarios, from small individual systems to large geothermal power plants. The modularity of ORC allows the creation of hybrid systems, integrating them with other energy sources or components to optimize power generation [18].

The energy access is becoming a key issue for sustainable development, the application of ORC represents a promising solution, especially in remote areas with limited connectivity to conventional energy networks [19]. Geothermal sources tend to be found in remote areas where conventional energy production methods may be inefficient or too costly. ORCs have lower complexity than some conventional power systems, making them less costly to transport and install in remote locations. This is essential in contexts where infrastructure may be limited and the cost of building and maintaining complex systems is high [20]. One of the key advantages of ORC in remote areas is its ability to efficiently utilize low-temperature geothermal resources, which expands its application area. This opens new perspectives for supplying energy to remote communities, even when conventional energy sources are inefficient or unavailable. Furthermore, ORC can be easily integrated into microgrids and off-grid systems, improving the reliability of power supply in remote areas that are not dependent on centralized grids.

One of the major challenges is the cost of installation and maintenance of the ORC system [21]. Despite the promise of this technology, the initial investment can be high, which creates a barrier to adoption, especially when budgets are tight. The cost-effectiveness of the system must be carefully evaluated and weighed against the long-term benefits it can provide. The variety of available substances requires careful analysis and testing to determine the best cycle performance parameters. The effectiveness of ORC is directly related to the properties of the selected working agent, and therefore the correct choice plays a key role in achieving best results. The working fluid in an ORC is often a binary system where two components interact to form a mixture that is optimized for thermodynamic processes. The choice of a particular binary fluid plays a determining role in the effectiveness of ORC. First of all, the thermodynamic characteristics of the components must be such as to ensure an efficient heat transfer process in each stage of the cycle, including expansion and condensation. A detailed consideration of the physical and chemical properties of each component of the binary fluid becomes a key factor in ensuring best ORC performance. This analysis helps to maximize the heat transfer efficiency and hence improves the overall performance of the ORC (Table 1).

ORC power generation system, which employs R245fa as the working fluid and a radial inflow turbine as the expander, provides significant information regarding how ORC systems operate and how efficient they are, particularly for geothermal energy [22]. Under optimal circumstances, the system attained a maximum thermal efficiency of 10.5% at a pressure of about 1.5 MPa. At this pressure, the radial inflow turbine achieved a maximum efficiency of 78%, proving its capacity to efficiently transform thermal energy into mechanical effort. The use of R245fa illustrates that working fluids with low toxicity and good thermodynamic characteristics may be utilized efficiently in geothermal systems, especially when system components are tuned for specific operating circumstances.

Table 1. Thermodynamic properties, health effects, and environmental safety of a range of potential candidates as working fluids

Liquid	Formula	Critical temperature (ºC)	Critical pressure (bar)	Molar mass (kg/kmol)	Toxicity	Flammability
Butane	C_4H_{10}	150.8	37.18	58.12	Low	Very high
Isobutane	i-C_4H_{10}	135.9	36.85	58.12	Low	Very high
Pentane	C_5H_{12}	193.9	32.4	72.15	Low	Very high
R245fa	$C_3H_3F_5$	154	36.51	134	Low	Not flammable

Source: compiled by the authors based on [11].

While R245fa shown encouraging results, comparative tests by Abbas *et al*. [23] indicated that the choice of working fluid has a considerable influence on the thermal efficiency of the ORC system. In their trials, alkanes like n-pentane outperformed hexamethyldisiloxane (HDMS) in terms of thermal efficiency. For example, n-pentane had a thermal efficiency of about 12.3%, whereas HMDS had roughly 9.8%. The greater performance of alkanes was ascribed to their advantageous thermodynamic features, such as increased latent heat of vaporization and reduced viscosity, which improve fluid dynamics in ORC systems. Although HMDS has advantages such as thermal stability and minimal toxicity, its lesser efficiency restricts its use in high-performance ORC systems.

Another technical challenge is the adaptation of the system to different operating conditions. Geothermal resources can vary in temperature, pressure, and composition, which requires flexibility in the ORC setting [24]. The technical solutions must be designed so that the system can function effectively under different geothermal conditions. Despite these challenges, the solution to which requires the combined efforts of engineers and economists, the benefits of ORC in geothermal energy stay significant. Environmental sustainability, scalability, and applicability in remote areas make this technology a promising renewable energy source, and addressing the technical and economic issues will only increase its impact on the future of the energy industry. Efficiency and economy play a key role in the design and operation of energy systems, combining exergy analysis with cost analysis is becoming an integral method. This approach provides important information for creating not only efficient but also economically feasible energy systems [25]. The main purpose of this combined method is to provide power system designers, engineers, and operators with all the necessary data for a detailed evaluation of thermodynamic characteristics and system performance.

Exergy analysis is a powerful tool in thermodynamic research, providing profound insights into the efficiency and energy performance of systems [26]. The basic idea of this method is to investigate energy losses and energy quality in processes, which makes it an integral part of technical analyses. One of the key aspects of exergy analysis is the isolation and categorization of exergy flows within a system. Exergy analysis also provides a more in-depth insight into the qualitative aspects of energy processes. By knowing which processes in the system have higher energy quality and which have lower energy quality, their use can be optimized. This approach is crucial when designing systems where efficiency plays a key role. Exegetics becomes a bridge between thermodynamics and real engineering solutions [27]. However, the successful application of exergy analysis requires careful calibration and customization of the methodology.

Therefore, exergy analysis is an indispensable tool for engineers and researchers seeking to develop efficient and sustainable energy systems, providing an in-depth understanding of energy processes and suggesting how to make them more productive and sustainable. This method effectively utilizes thermal energy from low-temperature geothermal sources to generate mechanical work. In light of the growing interest in renewable energy and the need to transition to more sustainable energy systems, the study considered a few recommendations on the prospects for using ORC to generate geothermal energy. The most notable outcomes of this study highlight the ORC's considerable potential for using low-temperature geothermal resources to create mechanical work. Another major result is ORC's resilience to changing geothermal conditions. The system's capacity to work consistently despite variations in geothermal source temperatures makes it ideal for geothermal resources with fluctuating heat outputs, such as hot springs and groundwater systems. This adaptability is critical in areas where geothermal temperatures fluctuate, allowing ORC systems to continue producing efficient energy even under less-than-ideal circumstances.

Heat exchanger inefficiencies and frictional losses inside the turbine were highlighted as possibilities for performance improvement, implying that future technical advancements might increase the system's total efficiency. Addressing these inefficiencies might considerably increase the system's cost-effectiveness and put ORC technology on the same level with other renewable energy systems. Another notable feature of ORC systems is their scalability, allowing them to be employed in geothermal plants of all sizes. This adaptability paves the way for the creation of modular ORC systems that may be placed in remote or difficult-to-reach regions, hence increasing access to renewable energy. The ability to incorporate ORC systems into off-grid and microgrid configurations also gives an energy alternative for remote populations where traditional energy systems may be prohibitively expensive or difficult to build.

4. DISCUSSION

Qyyum *et al*. [28] stress the importance of working fluids, thermal resources, and cooling agents in modern ORC systems. The temperature range of the geothermal source determines the working fluid used, emphasizing the need for more study. Thermal resources, such as low-temperature geothermal sources, require substantial research to determine the optimal operating conditions. Conventional steam systems are useless at low temperatures, whereas ORC optimizes these resources [29]. However, concerns with system stability and maintaining high performance at various temperatures require more research and technical solutions. Despite ongoing research, the commercial use of ORC remains limited. Future ORC uses include geothermal energy, solar installations, and low-temperature thermal resources. However, efficient commercialization requires consideration of both technological and economic feasibility, as well as system stability in a variety of conditions. In addition to increasing resource availability, the study's findings show that ORC systems are extremely responsive to changing geothermal conditions. Geothermal sources, particularly low-temperature ones, may provide varying heat outputs owing to seasonal or temporal fluctuations [30]. ORC systems have demonstrated their capacity to provide steady power even under these fluctuating settings, which is crucial for guaranteeing a consistent and reliable energy supply. This versatility is a significant advantage over traditional steam turbines, which often struggle to maintain efficiency when faced with changing temperatures. This discovery is consistent with the discoveries of Zhang *et al*. [31], who investigated the integration of geothermal energy into coal-fired power production systems utilizing ORC to improve efficiency and minimize greenhouse gas emissions.

Furthermore, the low noise and vibration levels of ORC systems make them excellent for use in ecologically sensitive regions. Traditional steam cycles can produce substantial noise and vibrations, which can harm nearby ecosystems, especially in protected natural areas like national parks [32]. ORC systems, on the other hand, operate quietly and with little vibration, minimizing their environmental effect. This property makes ORC technology excellent for places where environmental preservation is critical, such as nature reserves or other ecologically sensitive regions. Despite these advantages, the study acknowledges that numerous challenges must be solved in order to fully achieve the potential of ORC in geothermal energy systems. One of the most critical challenges is the economic feasibility of ORC systems, particularly in terms of installation and maintenance costs. While ORC technology provides long-term benefits for energy efficiency and environmental sustainability, the initial installation expense can be a barrier to broad adoption. This is consistent with the results of Meng *et al*. [33], who studied the economic performance of two-stage batch ORC and organic instantaneous Rankine cycle systems. Their findings indicate that, while ORC systems can provide considerable technological benefits, economic aspects such as installation costs and return on investment must also be addressed to ensure the system's long-term viability.

Orynbayev *et al*. [34] emphasized the necessity of developing power plant technology to boost the coefficient of performance (COP) of geothermal systems. Geothermal power plants' performance may be considerably enhanced by building more efficient turbines, generators, and heat exchangers, especially for off-grid applications that require reliable, autonomous energy supply [35]. Kozhageldi *et al*. [36] concluded that decentralizing power supply through the use of renewable energy sources, such as geothermal energy, is crucial for addressing energy shortages in rural or underdeveloped regions. ORC systems can help energy-deficient areas improve socioeconomically by offering a dependable and sustainable energy source that can be implemented in remote places. Furthermore, combining ORC systems with energy storage options, such as battery technology, can help regulate temporal changes in energy output and maintain a consistent power supply. The research also identifies potential prospects to integrate ORC with other advanced energy technologies, such as proton-exchange membrane systems for producing hydrogen, as proposed by Taheri *et al*. [37]. The combination of ORC and hydrogen production technologies may open up new paths for sustainable energy generation, especially as worldwide demand for clean hydrogen rises. This integration would enable ORC systems to contribute not only to geothermal power generation but also to the creation of clean hydrogen, thus strengthening their position in the renewable energy landscape.

Li *et al*. [38] determined, that the study of synergetic mechanism of organic instantaneous Rankine cycle with ejector is of significant interest in the context of improving the efficiency of geothermal energy. The organic instantaneous Rankine cycle is a variation of the classical Rankine cycle that has the potential to efficiently utilize low-temperature geothermal resources. The introduction of an ejector into the system adds a new element to the cycle mechanism, allowing for increased geothermal energy production. The ejector, acting as a rarefaction device, helps to more effectively reduce pressure in some parts of the cycle, which can improve system performance [39]. This synergistic mechanism provides new opportunities for optimizing the performance of geothermal plants, especially in cases with limited high-temperature source resources.

ORC systems have reduced maintenance costs than standard geothermal power systems because they can manage fluctuating temperature conditions, which reduces component wear and tear. Integrating ORC systems into decentralized energy solutions enhances energy availability in rural areas, promoting socioeconomic development and energy independence in communities without a stable electricity source. The capacity of ORC systems to generate renewable energy constantly increases their long-term economic sustainability. Furthermore, developments in ORC technology, such as improved turbine designs and optimized working fluids, are expected to increase efficiency and lower prices, making ORC systems more competitive with other renewable energy technologies. The initial expenses of ORC systems for geothermal power generation may be significant, but they offer lower operational expenses, environmental advantages, and long-term economic sustainability.

5. CONCLUSION

The prospects of using organic Rankine cycle for geothermal power generation represent a considerable potential for enhancing the sustainability and efficiency of renewable energy systems. Analyses of ORC applications in the context of geothermal resources, especially low-temperature resources, have revealed its ability to operate effectively under conditions where conventional technologies may be less effective. The study of best parameters of the cycle operation, development of technical recommendations on the choice of organic working bodies, revealed the improvement of ORC performance compared to conventional methods, which clearly indicates the prospects of application of this technology in the field of geothermal energy. Key results were identified that included ORC’s performance at low temperatures, its adaptability to diverse operating conditions, and the development of recommendations to improve overall system performance. These findings provide concrete practical recommendations to help optimize the use of ORC for geothermal energy. Exergy analysis provides a detailed understanding of the thermodynamic processes in a system, enabling an accurate assessment of its design and operation. At the same time, exergoeconomic analysis expands this view to include cost and efficiency aspects, which is essential to ensure the economic viability of energy projects.

The practical significance of this study is to open prospects for the development of more sustainable and cleaner systems in the field of renewable energy. Thus, the use of ORC represents a promising area in ensuring energy sustainability, reducing dependence on conventional energy sources and introducing innovative geothermal technology solutions. To advance geothermal power generation using ORC technology, further research must comprehensively evaluate its long-term sustainability, economic feasibility, and technological adaptability through comparative analyses with alternative power generation technologies, with a focus on developing modular and scalable systems capable of operating effectively across diverse geothermal source conditions.

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