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Thermodynamic, Exergy, and Environmental Evaluation of Hybrid Geothermal and Solar Energy-Based Organic Rankine Cycle Power Plant

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ABSTRACT
The increasing global energy demand and environmental concerns necessitate the development of efficient renewable energy systems. While geothermal and solar power plants have been studied separately, limited research exists on their integration and optimization. This paper advances the understanding of hybrid renewable systems by analysing a binary geothermal-solar power plant using an Organic Rankine Cycle (ORC), focusing on its thermodynamic and exergy performance. The system uniquely combines solar thermal collectors with geothermal resources, where a heat transfer fluid from the solar collector vaporizes the working fluid for power generation, while geothermal brine is maintained at 70°C before reinjection to prevent silica formation and source cooling. Through comprehensive exergy analysis, this study examines the environmental impact of energy exploration and generation using thermodynamic parameters. The research compares the system's performance using two working fluids, Toluene and Isobutane, revealing that working fluid selection significantly influences system energy efficiency and gross electricity generation. Results demonstrate that at a mass flow rate of 0.3 kg/s, Toluene achieves approximately 70% efficiency compared to Isobutane's 60%, providing valuable insights for optimizing hybrid geothermal-solar power systems.

***Keywords*: Hybrid Geothermal-Solar System, Organic Rankine Cycle (ORC), Thermodynamic Analysis, Exergy Analysis, Working Fluid Selection, Energy Efficiency.**

1. INTRODUCTION

Renewable energy is one of the most attractive sources of electricity supply, as the resource is virtually inexhaustible and has little negative impact on the environment. However, incorporating it into conventional power systems is typically challenging, given attributes such as relatively high capital costs per kW compared with traditional fossil sources like coal, oil, and gas. However, Sajid, Khan [1] say there are noticeable opportunities for future reliance on renewable technology to fuel the decades ahead of expansion. A major problem is that the primary sources of renewable power – solar and geothermal- are often far from the main power grid systems. Furthermore, solar power is an intermittent source of electricity that is only available during the day, limiting the need for hybrid systems to deliver electricity throughout the day. It is possible to consider the potential interaction between the solar and geothermal systems because the latter can act as a stabiliser for the former. The result in such a case may or may not be good depending on the place, the quality of the sources it has for modelling and the system that will be put in place.

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Research has shown that analysis of the integration of these renewable technologies has some achievement. For instance, the feasibility of geo-renewable systems may decrease due to a decrease in the temperature and pressure of its fluids, whereas the addition of work integration of solar energy functions [2,3]. A study on the integrated hybrid ORC systems established that it is possible to use a 90°C geothermal working fluid to preheat the organic fluid with a 150°C solar working fluid for superheating the working fluid [4,5]. Thus, the integrated approach provided an energy efficiency of 0.566 and an exergy efficiency of 0.156 [6]. Other research has focused on enhancing the effectiveness of ground heat exchangers with other accessories, such as cool towers and solar thermal collectors [7]. For instance, calculation of the control issues in digital technology with relation to ground-source photovoltaic heat pump (GSHP-PVT) has shown that the fuzzy logic control brought the slicing of the energy consumed per year by as much as 12% than if it was under the ON/OFF controls [8].

However, such research proves the feasibility of hybrid configurations yet typically assesses energy, economic, and environmental performance indicators independently. Such an approach can fail to capture important couplings between system elements, restricting the ability to identify the best balance between economic cost, energy demand, and emissions. This research aims to fill these gaps by providing a more comprehensive approach to analysing ORC-based hybrid solar-geothermal systems. This study aims to find an optimum design pattern that can help maximise power output and energy efficiency while reducing the adverse environmental effects by integrating the system's thermodynamic, economic, and environmental analysis. This analysis will compare pure geothermal cycles and those integrated with other turbines to identify the applicability of these cycles in limiting greenhouse emissions and augmenting the availability of clean energy compared with fossil fuels.

As the existing power generation system sustains high levels of greenhouse gas emissions, it calls for alternative and efficient methods. For these problems, two kinds of energy sources, solar and geothermal, are more viable to be implemented. This is where the problem lies: it is sometimes difficult to properly leverage both in a way that minimises the shortcomings of its sources – in the case of solar power, the intermittency of the resource; in the case of geothermal power, the geographical limitations on its efficiency. In doing so, this research will provide significant information into the synthesis of these resources to form hybrid systems, thereby offering meaningful contributions to the provision of sustainable energy to burgeoning energy demands without compromising the environment.

1.1 Aims and Scope of Study

The study has several key aims:

- To design a model of an Organic Rankine Cycle (ORC) that utilises both geothermal and solar energy sources.
- To assess this hybrid geothermal-solar ORC plant's thermodynamic, exergy, and environmental performance.
- To analyse how performance varies in response to different parametric adjustments.

This study will investigate two operational modes to provide the necessary heating and cooling for a building: one based solely on geothermal energy and a second that combines geothermal and solar energy. The Organic Rankine Cycle will be developed using Python and the CoolProp thermodynamic properties library, calibrating geothermal and solar data according to the power cycle's capacity range.

2. LITERATURE REVIEW

2.1 Solar-Thermal Technologies

The utility of solar technology can help ease energy gaps worldwide because it is a renewable resource available in ample quantities in the form of sunlight. The utilisation of low-grade thermal energy has been forecasted to be achieved using Solar ORC technology, which may need to be more efficiently harnessed through other means, as suggested by Kane, Larrain [9]. Another benefit of using a solar-thermal ORC system is that it becomes easier to store energy because power from the sun is not continually available. The advantages of the ORC power block concerning thermodynamics are low-level evaporation temperature, high fluid viscosity, low pressure, and a small value of the isentropic index. These properties decrease equipment size and dimensions, increase molecular weight, decrease peripheral velocities and mechanical strains and increase the overall system reliability [10].

Solar energy is easily available and does not add to the degradation of the atmosphere for greenhouse gases, making it ideal for substituting fossil fuels. It also adapts to environmental problems like sulphur oxide pollution and the impacts of global warming since it was developed by Prinn, Reilly [11]. For these reasons, much attention has been drawn to developing solar-thermal prototypes. Areas of interest are developing better production methods, choice of material, and fine-tuning performance modelling methods. More specifically, in the case of modelling solar ORC systems, analytical and computational tools are used to simulate performance impacts and enhance plant efficiency prediction effectively [12].

2.2 Organic Rankin Cycle

The Organic Rankine Cycle (ORC) process is like the Simple Rankine Cycle. Still, the working fluid used is a high molecular weight organic fluid, making it ideal for heat recovery from temp sources like industrial waste and solar thermal systems [13]. In ORC systems, an expander converts the heat captured at low temperatures into mechanical energy. Due to improvements in the economic and performance aspects, hermetic scroll compressors are employed in solar and biomass in reverse mode as expanders [14]. These scroll expanders transfer working fluid to generate energy in the expander region, an essential aspect of the ORC.

Jradi, Li [15] have examined a study on ORC-based micro-CHP systems with hermetic scroll expanders, revealing that raising the maximum inlet temperature and using two scroll expanders in series boosts electrical efficiency. Research with new types of scroll expanders for micro-scale ORC-based CHP systems revealed that the maximum electric power achieved by the expander is proportional to the pressure difference. However, the isentropic efficiency is optimum without fluid leakage under different operating conditions. Subsequent studies on the single-screw expanders in the context of ORC systems by Ziviani, Gusev [16] identified that the design aspects, such as the expander ratio and volume efficiency, depend greatly on the variables, including torque, dryness, and back pressure. All these depict that using the turbocharger, back pressure, and dryness negatively impacted the single-scroll expander efficiency, which went higher with rising torque before declining.

Models derived from the experiment, which include the polytropic exponent and isentropic models, have been used to predict the screw expander power output within the experimental value range [17]. In an experimental work by Ali Tarique, Dincer [18], the performance of the scroll expander was analysed and compared using input pressure, flow rate and volume ratio. The study also showed that isentropic efficiency varied from 0.5 to 0.64, depending on intake conditions, while volumetric efficiency could be greater than 0.9 when the load is optimised but reduced tremendously after that point. The experimental study of a regenerative ORC with an air-cooled condenser and an expander-generator unit coupled to a 120 °C heat source expels a net power of 920 W with energy and exergy efficiency of 8.5% and 35%, respectively.

2.3 Solar Collector

Solar-ORC system comprises a solar energy collector and an ORC subsystem, as highlighted by Loni, Mahian [19] and Ramos, Chatzopoulou [20]. It mainly comprises larger systems, including the parabolic trough collector (PTC), which is connected to the ORC subsystem with the evaporator turbine condenser and the pump. The operation starts with pumping the organic working fluid from the condenser to the evaporator, where solar-heated PTC collectors evaporate the organic working fluid into superheated vapour. This vapour enters the turbine, expands under lower pressure, and, in turn, rotates the turbine shaft, which is linked to an electric generator. During expansion through the turbine, the vapour is cooled and converted to liquid by heat disposal from the immediate environment. The fluid is then pumped back to evaporate again, hence the closure of the ORC looping system. See Figure 1 for a Schematic diagram.

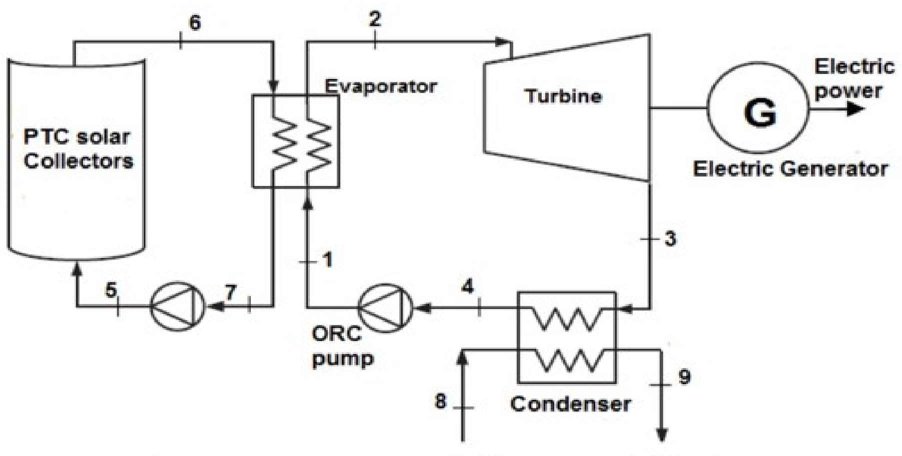

Figure 1. Schematic Diagram of ORC with Solar Collector

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2.4 Working Fluid for ORC

Selecting the right working fluid that fits well into the ORC system is very important, bearing in mind that low-temperature applications are necessary. The thermodynamic performance and efficiency of different fluids in ORC systems have been the research topic, especially for systems that use geothermal or waste heat [21]. Concerning low-temperature ORCs, working fluids have been evaluated based on the efficiency analysis and pinch point that air coolers, heat exchange properties, and working fluid OPTIMAL states for cycle structure [13]. Working fluids for geothermal-based ORC systems determine cycle design, where isobutane and R134a may be modelled in off-design conditions necessary for evaluating control measures [22]. More emphasis has been placed on fluid selection by Khennich and Galanis [23] for efficiency reasons involving operation with low-temperature sources. Due to their good thermal characteristics, two typical working fluids applied for ORCs are R134a and R141b. However, optimisations of subcritical ORCs are typically based on comparing with several other possible working fluids [24]. Astolfi, Romano [25] reviewed the progress of thermodynamic optimisations of binary ORC systems using medium- to low-temperature geothermal energy sources, further elaborating on the effects of fluid selection on performance and sustainability. These investigations demonstrate how some fluids, such as isobutane, can produce greater power under certain conditions. Regarding environmental characteristics of isobutane, it exhibits low toxicity and zero Ozone depletion value. Nevertheless, it may be a concern for isobutane since high pressures in the turbine may have operational problems with isobutane, thus restricting its use in some ORC systems [26].

3. METHODS AND MATERIALS

This study systematically divides the project into two parts: thermodynamic analysis and energy-environmental analysis. Figure 2 provides an overall study flow chart.

3.1 Thermodynamics Analysis

The first step in thermodynamic analysis is computing the unknown temperature, pressure, and enthalpy values. This is called thermodynamic modelling. The first law analysis is carried out after thermodynamic modelling. The energy, mass balance, and material equations are the fundamental equations of first law analysis, and they can be written according to the balances of mass Equation (1) and energy Equation (2). The energy analysis based on the second law of thermodynamics is carried out after the first law analysis.

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \qquad (1)$$

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = 0 \qquad (2)$$

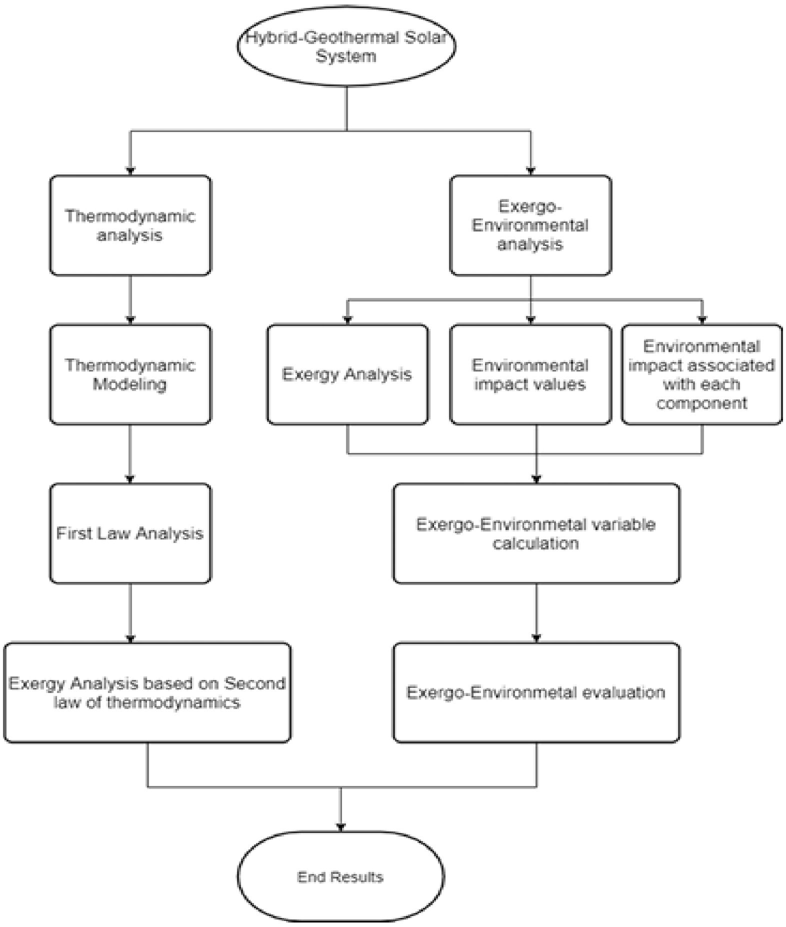

Figure 2. Project Workflow

The equation of thermal equilibrium of the evaporator is:

$$\dot{m}_{geo}.\,(h_{geo\ in} - h_{geo\ out}) = \dot{m}_{orc}.\,(h_{orc\ out} - h_{orc\ in}) \quad (3)$$

Where $\dot{m}_{geo}$ is the mass flow rate of geothermal fluid, whose value is 55.56 kg/s, and $\dot{m}\ orc$ is the mass flow of organic fluid, whose value is 30 kg/s. $h_{geo\ in}$ is the enthalpy of geothermal fluid at the inlet, and $h_{geo\ out}$ is the enthalpy of geothermal fluid at the outlet. $h_{orc\ out}$ is the enthalpy of working fluid at the outlet, and $h_{orc\ in}$ is the enthalpy of working fluid at the inlet.

The equation of the thermal equilibrium of the condenser is:

$$\dot{m}_{orc}.\,(h_{orc\ in} - h_{orc\ out}) = \dot{m}_{water}.\,(h_{water\ out} - h_{water\ in}) \quad (4)$$

Where $\dot{m}_{water}$ is the mass flow rate of water in a water-cooled condenser.

The power of the turbine is given by:

$$\dot{W}_t = \dot{m}_{orc}.\,(h_{in} - h_{out}) \ (5)$$

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3.2 Exergy-Environmental Analysis

It is carried out to ensure that the energy production system under consideration does not considerably affect the environment. It is comprised of three steps. The first step is the detailed exergy analysis of the system. In the second step, environmental impact values are computed using appropriate methods. In the last step, the environmental impact of each component is calculated. The exergy-environmental variables are computed afterwards, and the exergy-environmental evaluation is carried out. The values of Enthalpy and Entropy based on the Temperature and Pressure are calculated as:

$$\dot{E_i} = \dot{m} \, . (h_i - h_i[0] - T[0] \, . (s_i - s_i[0])) \quad (10)$$

Where $\dot{m}$ is the mass flow rate of fluid, h is the enthalpy, s is the entropy, and i is the state.

The exergy destruction is according to the following formula for each component. For the turbine:

$$\dot{E_d} = 0 + \dot{E_{in}} - \dot{E_{out}} - \dot{W} \quad (11)$$

For pumps:

$$\dot{E_d} = 0 + \dot{E_{in}} - \dot{E_{out}} + \dot{W} \quad (12)$$

The total exergy destruction (Ed) is obtained by adding the exergy destruction of the components. Similarly, the environmental impact and exergy of each stream are related as:

$$\dot{B_i} = b_i . \dot{E_i} \quad (13)$$

The exergy-environmental evaluation is carried out afterwards. The results of isobutane are compared with those of toluene.

3.3 Model Layout

Solar energy is an intermittent source of energy. Geothermal energy is considered more reliable because it is available regardless of weather conditions. Geothermal energy is also considered an endlessly renewable source, as the earth's core is always hot. Integrating both renewable energy sources results in a hybrid system that generates stable and uninterrupted energy. In this study, an integrated geothermal solar system was modelled. The schematic of the proposed system is given in Figure 3.

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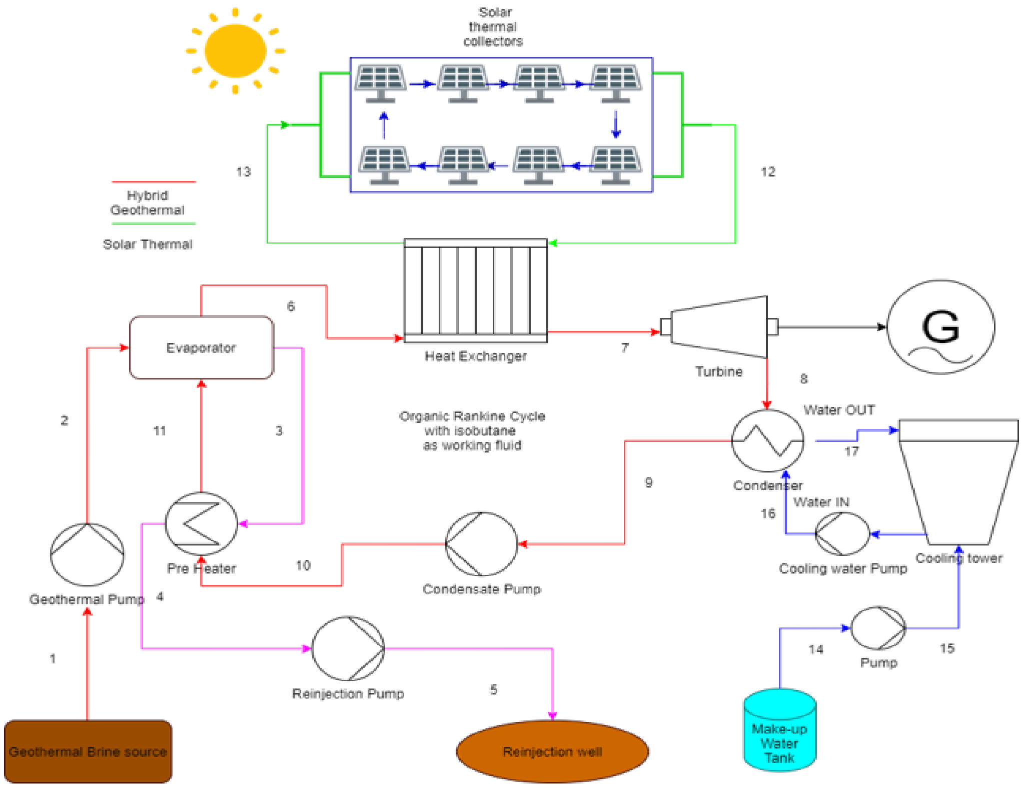

Figure 3. Schematic Diagram of Hybrid Geothermal Solar System

Geothermal energy is believed to have a more significant energy production potential. It is considered more reliable because of its availability regardless of weather conditions. The Ulu Slim, Perak, has a geothermal resource potential of 148 MW, according to a survey by the Department of Mineral and Geoscience and SEDA. The other sites in Peninsular Malaysia with geothermal resource potential are Lojing in Kelantan, Ulu Langat, Betang Kali in Selangor, and Sungai Denak in Perak. In the Sabah/Labuan region, the areas with geothermal potential are Apas Kiri, Twau, Sabah, and Segaria-Sungai Jipun Gunung Pock in Kunak. The Hybrid Geothermal Cycle is indicated with a red arrow in Figure 4. The geothermal fluid is pumped from a natural reservoir (Geothermal Brine Source), and the heat from the geothermal fluid is transferred to the working fluid (Isobutane) through an evaporator. The geothermal fluid enters the system at 90 °C and at 2.5 bar. The geothermal fluid is then returned to the reservoir using a reinjection pump. The salt is released at a minimum temperature of 70 °C to avoid the formation of silica and geothermal source cooling.

The organic Rankine Cycle is like that of the ordinary Rankine Cycle. The only variance is that organic fluid with a comparatively lower boiling point produces vapour instead of water. The vapours then expand through a turbine, producing electricity. The working fluid is selected by considering boiling and freezing points. Ideally, the boiling point of the working fluid should be lower for faster vaporisation, and the freezing point of the working fluid should be lower, so it does not solidify throughout the process. The working fluid used for this study is Isobutane. The boiling point of Isobutane makes it suitable for use as a working fluid in the Organic Rankine Cycle. The heat from the geothermal brine evaporates the working fluid. The working fluid flows through a heat exchanger afterwards. The electricity is then produced after expanding the steam through an ORC turbine. Finally, it is cooled using a water-cooled condenser. The condensate pumps the working fluid into the preheater, where it re-enters the cycle.

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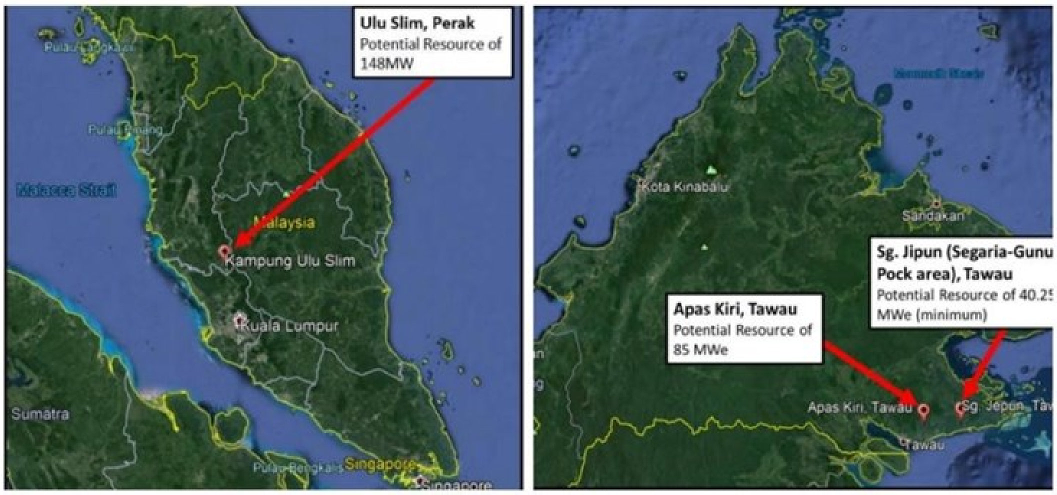

Figure 4. Areas Having Geothermal Potential

The solar thermal panels generate heat. The solar thermal collectors concentrate and collect the sun's thermal energy, which is then used to raise the temperature of the 'Heat Transfer Fluid,' which flows through the absorber tubes. Solar thermal collectors are considered reliable because these can even work on cloudy days. Moreover, the water heated by solar thermal energy can later be stored in hot water storage tanks. Solar thermal collectors usually comprise reflective glass, absorber tubes, and inner glass. The breakdown of a solar thermal collector is given in Figure 5.

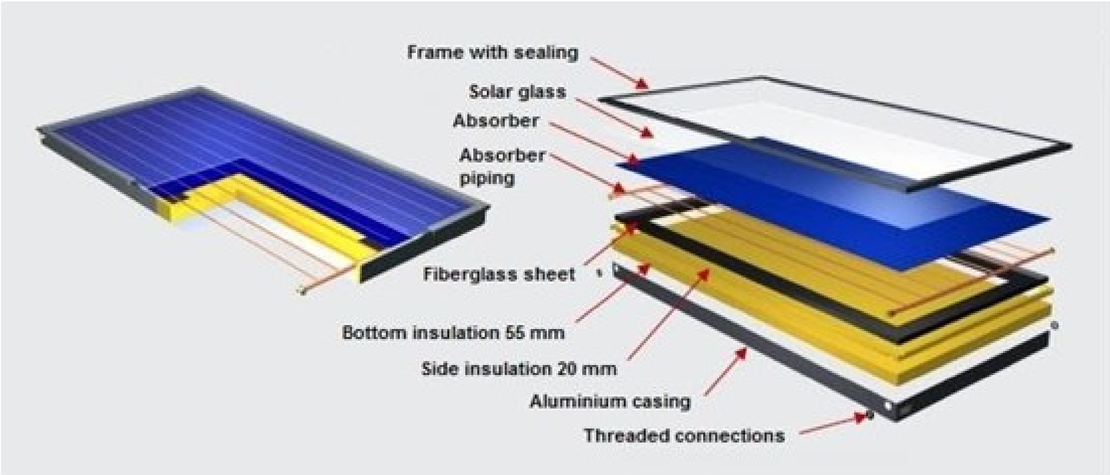

Figure 5. Solar Thermal Collector

4. RESULTS

The design programming is done in Python to evaluate the suggested mode more precisely, and the findings are given separately from the simulation. The results indicate the most critical design parameters selected according to Dermata, Schina [27].

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Table 1. Parameter of Model Layout

Parameters	Value
The mass flow of geothermal fluid (kg/s)	55.56
The mass flow of organic fluid (kg/s)	0.3
The temperature of Geothermal fluid (°C)	90
The pressure of Geothermal fluid (bar)	2.5
The minimum temperature of returning geothermal fluid (°C)	70
Ambient Temperature (°C)	25
Maximum temperature [K]	575.0
Maximum pressure [Pa]	35000000.0
Critical point temperature [K]	407.817
Critical point density [kg/m3]	225.5
Critical point density [mol/m3]	3879.756788283995
Critical point pressure [Pa]	3629000.0

The system performance is affected by the design parameters. Higher ORC efficiency is obtained at higher temperatures, but the efficiency of solar collectors reduces at higher temperatures due to increased mean temperature. The effect of increased source temperature is also examined in this study. The increased heat source temperature reduces electricity production due to reduced solar efficiency. The solar collectors operating at higher temperatures are useless for overall system performance. This needs to be addressed by using high flow rates in the solar field. The increased heat source temperature also led to decreased exergy efficiency.
The choice of working fluids influences the exergy efficiency and the net electricity production. In this study, Isobutane is used as a working fluid, and the exergy efficiency and the net electricity production with turbine inlet temperature and pressure are computed. These are then compared with the exergy efficiency of toluene.

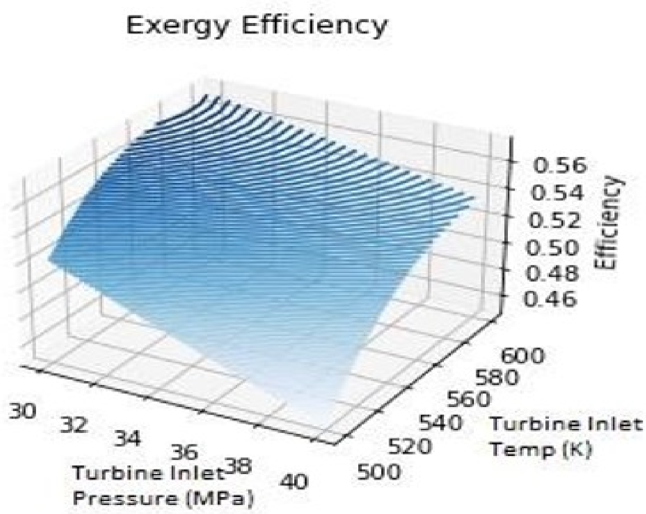

Figure 6. Exergy Efficiency of Isobutene

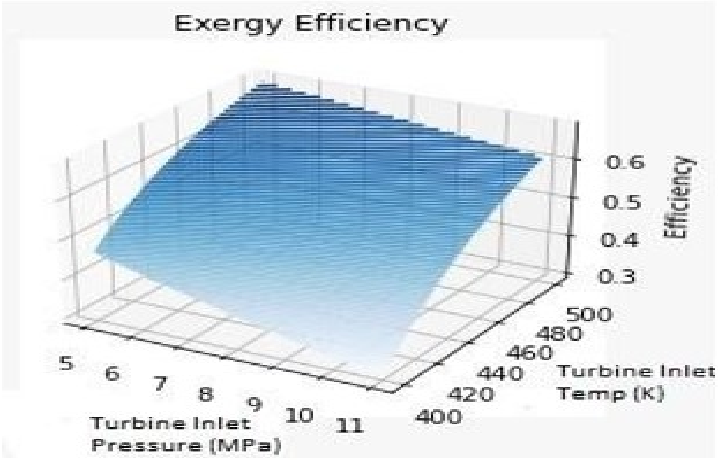

Figure 7. Exergy Efficiency of Toluene

The turbine output power is plotted against the range of mass flow rate of organic fluid. The range of organic fluid is taken from 0.1 to 0.7 (kg/s).

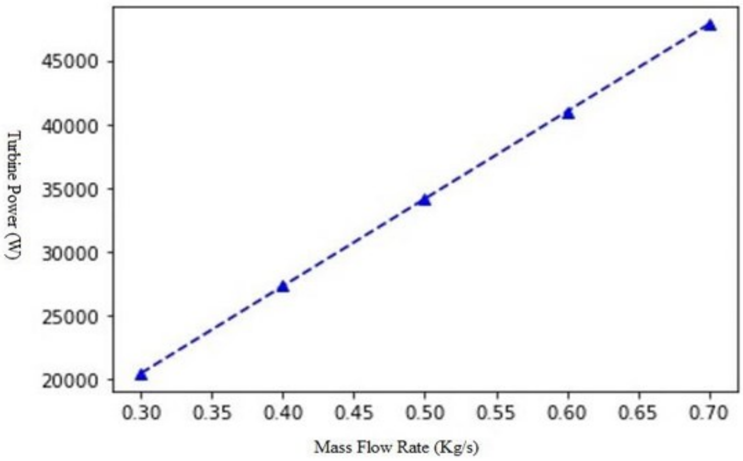

Figure 8. Turbine power and Mass flow rate of organic fluid

Exergy efficiency is plotted against the same mass flow rate range; the results are shown in Figure 9.

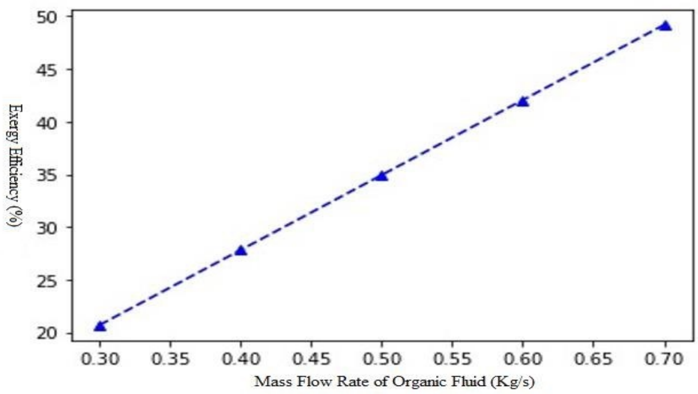

Figure 9. Exergy efficiency and Mass flow rate of organic fluid

The graph depicts an inverse relation between the geothermal fluid inlet temperature and turbine power. Increasing the geothermal fluid inlet temperature decreases the turbine power and vice versa. With every 10-degree rise in

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the temperature of the geothermal brine inlet, the turbine power decreases by 12%. An increase of 12% is seen in the turbine power if the temperature of the geothermal fluid is reduced by 10 degrees.

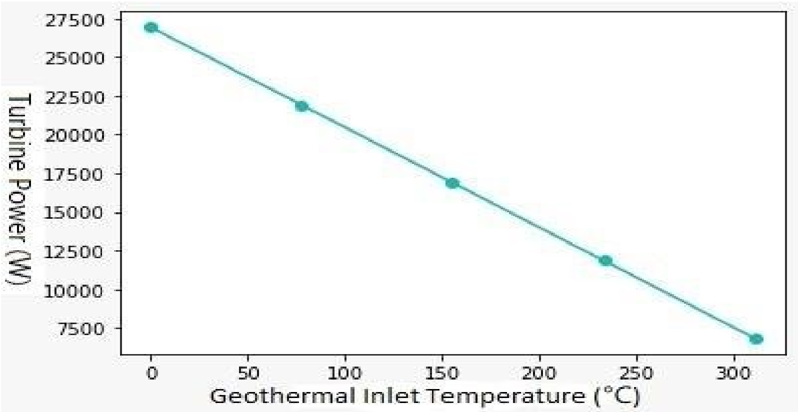

Figure 10. Effect of Geothermal Inlet Temperature on Turbine Power

Solar collector temperature has a direct relation with exergy efficiency. An increased solar collector temperature results in an increased exergy efficiency. The exergy efficiency (%) decreases with a decrease in solar collector temperature (K).

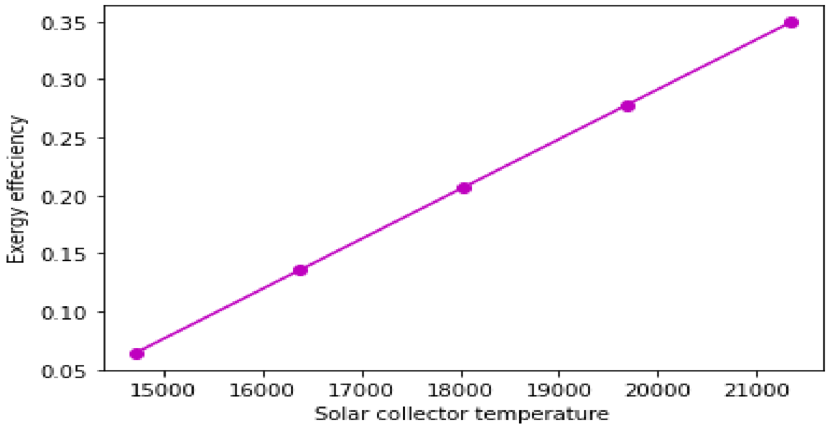

Figure 11. Effect of Solar Collector Temperature on Exergy Efficiency

The turbine's inlet temperature affects its net electricity production. The increased temperature of the turbine inlet benefits the overall efficiency and the exergy efficiency until the inlet pressure of the turbine is not too low. The increased inlet turbine temperature can improve the overall performance of the ORC system.

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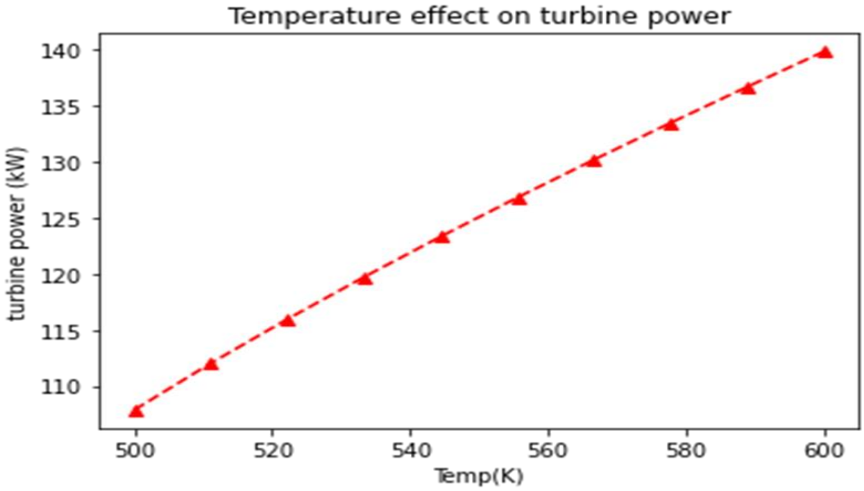

Figure 12. Effect of Temperature on Turbine Power

The influence of the turbine's inlet pressure on the net electricity production differs with different working fluids. The working fluids have a moderate boiling point, and the pressure is optimum for maximum net power output. The turbine's high inlet temperature can monotonously increase the net electricity production with the increased turbine inlet pressure.

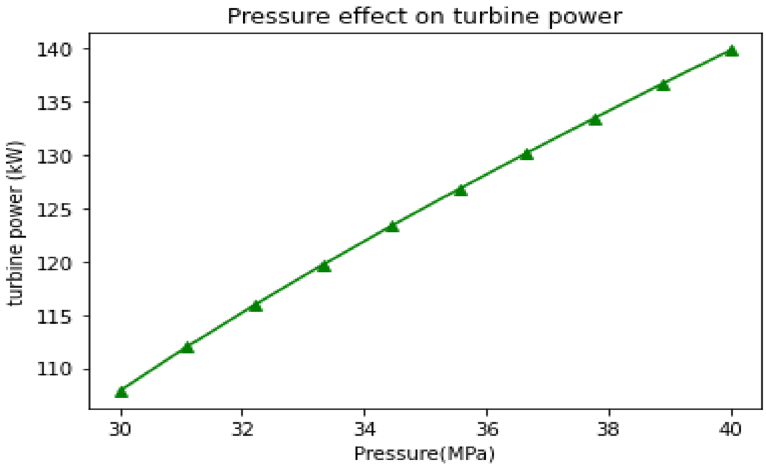

Figure 13. Effect of Pressure on Turbine Power

As indicated in Figure 14, the organic Rankine cycle's net power plotted against the temperature and pressure values is more significant than the maximum limits.

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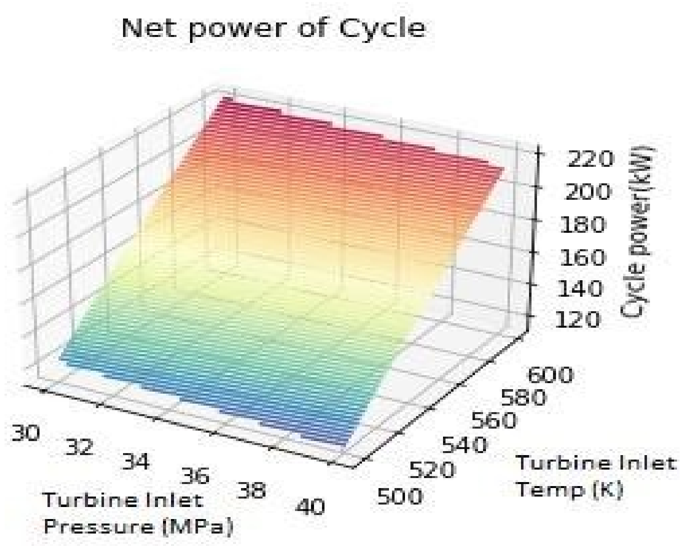

Figure 14. Net power of the cycle (Isobutane)

The net power of the organic Rankine cycle for Toluene plotted against the values of temperature and pressure taken more significantly than the maximum limits as indicated in Figure 15.

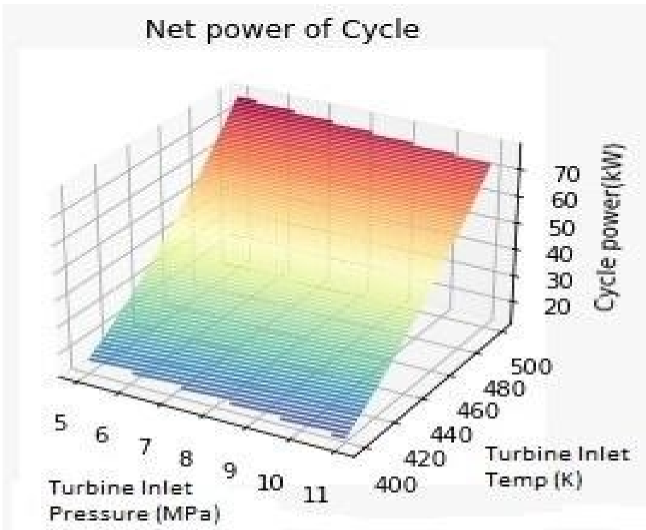

Figure 15. Net power of the cycle (Toluene)

The valuable outputs of the system proposed in this study are exergy efficiency and net electricity production. The choice of working fluid affects both outputs. The same design parameters are used for two different organic fluids (Toluene and Isobutane), and the exergy efficiency and the net electricity production are compared. The results of net electricity production, overall efficiency, and exergy efficiency for Toluene and Isobutane for a range of organic fluid mass flow rates are given in Tables 2 and 3.

Table 2. Data Analysis of Isobutene Fluid

Isobutane					
Mass flow (kg/s)	**Turbine power (W)**	**Inlet temperature at HRS (K)**	**Net Electricity (kW)**	**Overall Efficiency (%)**	**Exergy Efficiency (%)**
0.1	6829.495	426.490	11700.451	46.286	22.667
0.2	13658.990	436.490	16345.146	54.921	28.793
0.3	20488.485	446.490	20989.841	60.556	39.919
0.4	27317.980	456.490	25634.535	69.192	50.045
0.5	34147.476	466.490	30279.230	75.827	62.171

Table 3. Data Analysis of Toluene Fluid

Toluene					
Mass flow (kg/s)	**Turbine power(W)**	**Inlet temperature at HRS (K)**	**Net Electricity (kW)**	**Overall Efficiency (%)**	**Exergy Efficiency (%)**
0.1	21720.098	608.199	14191.146	48.844	24.488
0.2	32580.148	618.199	22403.536	60.576	33.088
0.3	43440.197	628.199	30615.926	70.308	45.687
0.4	54300.247	638.199	38828.315	81.040	58.287
0.5	65160.296	648.199	47040.705	89.772	67.886

When compared to the two different fluids, Toluene is more efficient than Isobutane. Isobutane's overall efficiency is only 75.8% when the mass flow rate is 0.5, whereas Toluene has 89.7%. At the parameter mass flow rate of 0.3 in the current study, the overall efficiency of the ORC power plant using Isobutane is 60.5%. However, if Toluene is used, the efficiency increases to 70.31%, which is more efficient. Therefore, it is better to use Toluene as the working fluid.

5. DISCUSSION

The findings of this study confirmed that incorporating geothermal and solar energy sources within ORC improves the thermodynamic efficiency, specifically if Toluene is applied as the working fluid. This efficiency gain parallels previous literature emphasising hybrid systems' effectiveness in low-grade heat recovery. For example, Astolfi, Romano [25] reported similar enhancement trends in the energy output of ORC systems using low-temperature heat sources; this plays an important role for renewable energy systems because efficiency should be optimised under different operating conditions. According to Calise, Cappiello [2], the constant geothermal heat source is supplemented by the fluctuating high-temperature solar resource, making steady power production possible in changing solar conditions. The present study supports the thermodynamic feasibility proposal of geothermal-solar integration for low-grade energy recovery as a sustainable medium for achieving efficiency improvements in ORC applications for renewable energy.

The exergy analysis of this study indicates that Toluene yields better exergy efficiency and environmental performance than Isobutane, emphasising the role of the working fluid. Past work has proved that to ensure low environmental impact. First, the working fluids must have high thermal stability and, second, a low GWP, with Toluene being preferred in the current ORC system. Schuster, Karellas [24] noted that low-GWP fluids considerably reduce the environmental impact, not a kernel yield. Likewise, Khennich and Galanis [23] paid much attention to using eco-friendly fluids in ORC cycles to meet the intention of climate change, which is also the focus of the present work. This work supports the idea that material selection for working fluids is critical for sustainable engineering in hybrid energy systems because Toluene possesses a higher exergy efficiency and a minor negative environmental footprint.

To further understand that key parameters influence the ORC Systems' performance, the parametric analysis shows that, for instance, the depth of the geothermal fluid inlet and solar collector temperatures is vital. In particular, the study established that higher levels of geothermal fluid temperature directly lower turbine power, complementing Ziviani, Gusev [16]'s conclusion of like performance degradation under high-source temperature working fluids thermal stress. Also, the increase of TSC with the energetic efficiency is in agreement with the study by McTigue, Castro [28], who found that high TSC values led to the collectors' increased energy output. Still, the efficiency needs to be regulated to avoid efficiencies and reductions. These results show that accurate parametric control is crucial for achieving sustained high efficiency in geothermal-solar hybrid ORC systems, highlighting optimisation approaches in renewable energy conversion to ensure robust efficiency, and system performance stability.

6. IMPLICATIONS AND FUTURE RESEARCH

The findings of this study have several important implications. The significant relationship between the efficiency gains from integrating geothermal and solar energy sources in the ORC system, and the superior performance of Toluene as the working fluid, suggests that organizations should prioritize optimizing working fluid selection and hybrid renewable energy integration to maximize thermodynamic efficiency. This aligns with previous research emphasizing the importance of hybrid systems for low-grade heat recovery.

The results also indicate that carefully controlling parameters like geothermal brine inlet temperature and solar collector temperature is critical for maintaining high efficiency and stable performance in these integrated ORC systems. Implementing strategies to optimize these factors could help organizations improve their renewable energy conversion capabilities and remain competitive.

The sample was drawn from a single geographic region, which may limit the generalizability of the results. Replicating this study in other contexts would strengthen the external validity. The study also did not account for several potentially relevant contextual factors, such as ambient conditions and system maintenance procedures, which could influence the relationships examined. Building on these findings and limitations, several promising avenues for future research emerge. First, longitudinal investigations are needed to better understand the causal mechanisms underlying the dynamic interplay between working fluid selection, renewable energy source integration, and ORC system performance over time.

Second, future studies should explore the boundary conditions and contingency factors that may moderate the observed relationships, such as the role of ambient conditions and maintenance practices. Investigating these moderators could provide a more comprehensive understanding of the factors shaping ORC system efficiency. Third, researchers should consider adopting mixed method approaches that combine quantitative and qualitative data sources. Qualitative insights could offer a richer, more nuanced understanding of the experiences and processes driving the phenomena of interest. Finally, given the practical implications, future research should evaluate the efficacy of interventions or programs designed to enhance the performance of integrated geothermal-solar ORC systems. Assessing such initiatives would contribute to translating research findings into impactful organizational practices.

7. CONCLUSION

This study analyses an integrated hybrid geothermal-solar system using an organic Rankine cycle (ORC) to produce electricity. The system utilises both geothermal and solar thermal energy sources. The heat transfer fluid from the solar thermal collector vaporises the working fluid, which is then expanded in a turbine to generate power. The geothermal brine is also leveraged, preheating to 70°C before reinjection to avoid silica formation and source cooling.

This study's thermodynamic and exergy environmental analyses demonstrate that the choice of working fluid significantly impacts the system's energy efficiency and net electricity production. The results show that Toluene, with an overall efficiency of around 70% at a mass flow rate of 0.3 kg/s, performs better than Isobutane, which has an efficiency of 60% at the same flow rate. Furthermore, the study reveals an inverse relationship between geothermal brine inlet temperature and turbine power and a direct relationship between solar collector temperature and exergy efficiency. These findings highlight the importance of careful working fluid selection and system optimisation to maximise the performance of integrated hybrid geothermal-solar ORC systems.

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