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Utilizing Geothermal Energy in Waw an-Namus, South Libya, for Electricity Generation Using Binary Cycle Technology

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Abstract

This study examines the feasibility of geothermal energy extraction in the Waw an-Namus volcano area in Libya and its transformation into electricity using Organic Rankine Cycle (ORC) technology. Waw An-Namus is located on the eastern side of Fezzan, Libya. Given the volcanic history of Waw an-Namus and its proximity to the Sirt Basin, which is known for thermal activity, it presents a promising geothermal resource. The performance of geothermal power plants based on a binary cycle system using R245fa as the working fluid was studied using detailed thermodynamic models and simulations within MATLAB for a geothermal temperature range of 100-180°C. When the geothermal fluid temperature is 140°C and the mass flow rate is 50 kg/s, the system produces a net electric power of approximately 5.49 MW with thermal and exergy efficiencies of 34.3% and 135%, respectively. These results were confirmed by the data, and the economic analysis performed also demonstrated that the technology is economically viable compared to traditional power generation, achieving a levelized cost of energy (LCOE) of $0.036/kWh. Sensitivity analysis revealed that the system performance is primarily determined by the geothermal temperature and pressure ratio, with the optimal pressure ratio falling within the 5–6 range. This study serves as a valuable resource for constructing a renewable energy framework in Libya and advancing the utilization of geothermal power generation from low- and medium-temperature resources in volcanic zones. This is particularly significant in Libya, where there is little to no documented geothermal exploration or utilization.

Keywords: Geothermal power, Binary cycle, Organic Rankine Cycle, Waw an-Namus, Libya, Renewable power, ORC, R245fa, Volcanic caldera, MATLAB simulation.

Introduction

1.1 Background and Motivation

Libya is a large country with abundant natural resources, but it continues to struggle to meet the growing demand for electricity while implementing new sustainable energy systems. Libya continues to obtain most of its energy from fossil fuels. Energy diversification is a critical priority, considering the aging energy infrastructure and geopolitical instability in Libya. Among the available renewable energy options, geothermal energy may best serve Libya's sustainable development, reduce greenhouse gas emissions, and improve energy security. Geothermal energy is one of the most reliable renewable energy sources.

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Geothermal power plants can provide baseload power without requiring fossil fuels, and unlike solar and wind, they operate at capacity factors exceeding 90%. This makes geothermal power stations superior to solar and wind energy in terms of grid stability and energy supply reliability. The global geothermal power capacity has grown tremendously to over 15 GW, with countries such as Iceland, New Zealand, and Kenya successfully harnessing geothermal energy

1.2 Geothermal Potential in Libya

Waw An-Namus is a Quaternary volcanic caldera located at 24.906°N, 17.772°E in the southeastern part of the Libyan Desert, presenting a unique geothermal prospect for exploration. It is a dormant caldera that is 4 km wide and has a central cinder cone that is 120 m tall. It is surrounded by several saline lakes. Geological studies and volcanic history suggest volcanic activity during either the Pleistocene or Holocene epoch, with potassium-argon dating placing the caldera at approximately 200,000 years before the present, indicating volcanic activity within the last several hundred thousand. The history of this site and the fact that there is thermal activity in the area make it a good candidate for geothermal energy extraction. Libya has yet to explore its thermal energy resources, although Waw an-Namus holds significant potential, and northern Africa possesses considerable geothermal energy resources. The Sirt Basin is one of the largest unexploited geothermal sedimentary basins in Africa, with power-generation potential. The geothermal gradients in the Sirt Basin range from 40 to 60°C/km, with heat flow values between 80 and 130 mW/m^2, which is considerably higher than the global mean geothermal heat flow of 60 mW/m^2. This makes the Sirt Basin a viable candidate for the development of geothermal resources.

1.3 Binary Cycle Technology

Binary-cycle power plants are considered among the most promising systems for harnessing low- to medium-temperature geothermal resources (85–180 °C) [3]. Binary systems convert lower-grade thermal energy into electricity more efficiently than traditional flash steam plants, which require resource temperatures >180 °C [4].

In a binary cycle, a closed-loop configuration is employed using a secondary working fluid that vaporizes at a lower temperature than water. Common working fluids include organic compounds such as R245fa, isobutane, and isopentane. Unlike conventional steam Rankine cycles, Organic Rankine Cycles (ORC) utilize organic working fluids [2].

The binary system consists of two separate fluid loops: the primary loop contains geothermal brine, while the secondary loop contains the organic working fluid. In the evaporator, heat exchange occurs as thermal energy from the geothermal fluid vaporizes the working fluid. The vaporized organic fluid expands through a turbine to generate electricity. It is then condensed and pumped back to the evaporator, thereby completing the cycle [9].

1.4 Research Objectives

This study aims to achieve the following objectives:

1. Assess the geothermal resource characteristics of Waw an-Namus using available geological and geophysical data.
2. Develop a thermodynamic model of a binary-cycle geothermal power plant under the specified resource conditions.
3. Conduct MATLAB simulations to evaluate system performance across a range of operating parameters.

4. Assess the economic viability and levelized cost of electricity generation.
5. Determine optimal operating conditions and system design recommendations.
6. Contribute to the body of knowledge on geothermal energy development in North Africa.

2. Geological Setting and Resource Assessment

2.1 Regional Geology

Waw an-Namus belongs to the Tibesti volcanic province, one of several regions exhibiting extensive Cenozoic volcanism. The area has undergone multiple phases of volcanic activity associated with rifting processes and mantle plume dynamics. These include basaltic lava flows, pyroclastic deposits, and cinder cones, indicating both effusive and explosive eruptive styles.

Additional evidence of elevated geothermal gradients in the broader region is observed in the Sirt Basin, located approximately 300 km north of Waw an-Namus. According to Mansour et al. (2019), the Sirt Basin exhibits geothermal gradients of 40–60 °C/km, with localized values reaching up to 60 °C/km. Heat flow values range from 80–130 mW/m², among the highest recorded on the African continent. These elevated temperatures are attributed to lithospheric thinning associated with Mesozoic rifting and ongoing tectonic activity.

2.2 Volcanic Features of Waw an-Namus

Waw an-Namus contains a well-preserved volcanic caldera with distinctive morphological features [8]. The caldera rim rises approximately 100 m above the surrounding plain and is composed of basaltic tephra and fragmented lava materials. The central cone reaches a height of 120 m and represents the main eruptive center.

Three saline lakes located on the caldera floor are considered potential indicators of subsurface geothermal heat. The volcanic lithology is dominated by alkali basalt and phonolitic compositions, characteristic of intraplate continental volcanism. Lava flows are clearly observable, and the limited degree of erosion suggests relatively recent volcanic activity, although no historical eruptions have been documented [8].

2.3 Geothermal Resource Estimation

Based on regional geothermal gradients and volcanic characteristics [8], the geothermal resource at Waw an-Namus is estimated as follows:

- Geothermal gradient: 45–55 °C/km (estimated)
- Heat flow: 90–120 mW/m² (estimated)
- Reservoir temperature at 2000 m depth: 120–145 °C
- Reservoir temperature at 3000 m depth: 160–200 °C
- Expected fluid chemistry: moderate to high salinity (brackish to saline)

Based on these estimates, Waw an-Namus is likely to possess sufficient thermal potential for binary-cycle power generation at an optimal depth range of 2000–3000 m [14], [22], [21].

3. Research Methodology

3.1 System Configuration and Operating Concept

The proposed binary-cycle geothermal power plant consists of two separate fluid loops designed to extract geothermal heat and convert it into electricity while maintaining complete physical separation between the geothermal brine and the power generation system. This configuration enables emission-free electricity generation within a closed-loop system, thereby minimizing environmental impacts.

Figure 1 illustrates a typical configuration and the operating principle of binary-cycle geothermal power plants. The system comprises the following main components:

1. Production Well: Extracts high-temperature geothermal brine (typically 100–180 °C) from the subsurface reservoir.
2. Heat Exchanger (Evaporator): Transfers thermal energy from the geothermal brine to the secondary working fluid (organic fluid). The working fluid vaporizes at a lower temperature than water due to its favorable thermodynamic properties.
3. Turbine–Generator Unit: High-pressure vapor expands through the turbine, driving an electrical generator to produce electricity.
4. Condenser: Condenses the working fluid vapor back into liquid form after expansion in the turbine.
5. Working Fluid Pump: Pressurizes the condensed working fluid and recirculates it to the evaporator.
6. Injection Well: Reinforces reservoir sustainability by reinjecting cooled geothermal brine into the subsurface formation to maintain reservoir pressure.
7. Cooling System: Typically air-cooled in arid regions such as Waw an-Namus to reduce or eliminate water consumption.

Operating Principle: Hot geothermal brine is extracted to the surface through the production well and directed to the heat exchanger, where thermal energy is transferred to the working fluid (R245fa in this study). The cooled brine is subsequently reinjected into the reservoir via the injection well. The vaporized working fluid expands through the turbine–generator unit to produce electricity. It is then condensed and pumped back to the evaporator, completing a continuous closed-loop thermodynamic cycle.

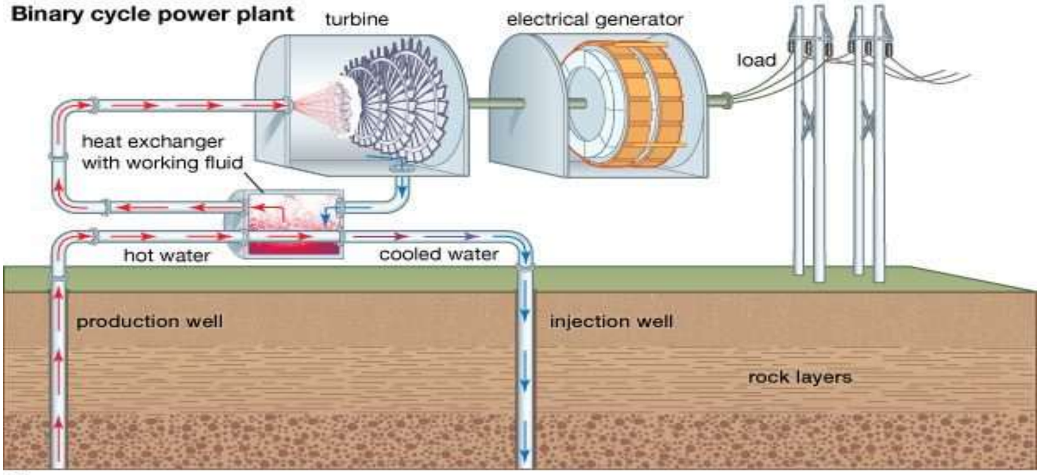

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Figure 1. Schematic diagram of a binary-cycle geothermal power plant

3.2 Thermodynamic Model

The following basic equations and assumptions form the thermodynamic analysis:

- Q̇~in~ = heat transfer rate into the system (kW)
- ṁ~geo~ = mass flow rate of geothermal fluid (kg/s)
- c~p, geo~ = specific heat capacity of geothermal fluid (kJ/kg·K)
- T~geo, in~ = inlet temperature of geothermal fluid to evaporator (°C or K)
- T~geo, out~ = outlet temperature of geothermal fluid from evaporator (°C or K)

- ṁ~wf~ = mass flow rate of working fluid (kg/s)
- h~3~ = specific enthalpy at turbine inlet (kJ/kg)
- h~2~ = specific enthalpy at evaporator inlet (kJ/kg)
- Ẇ~turbine~ = power output from turbine (kW)
- h~4~ = specific enthalpy at turbine outlet (kJ/kg)
- η~turbine~ = isentropic efficiency of turbine (%)
- η~generator~ = efficiency of generator (%)
- Ẇ~pump~ = power input to pump (kW)
- v~1~ = specific volume of working fluid at pump inlet (m³/kg)
- P~2~ = pressure at pump outlet (kPa)
- P~1~ = pressure at pump inlet (kPa)
- η~pump~ = isentropic efficiency of pump (%)
- Ẇ~net~ = net power output from the system (kW)
- η~thermal~ = thermal efficiency of the cycle (%)
- η~exergy~ = exergy efficiency of the cycle (%)
- Ex~geo~ = exergy of geothermal heat input (kW)
- T~0~ = ambient temperature (K)
- T~geo~ = mean temperature of geothermal heat source (K)

3.2.1 Energy Balance Equations

For the evaporator (heat exchanger):

$\dot{Q}_{in} = \dot{m}_{geo} \times c_{p,geo} \times (T_{geo,in} - T_{geo,out}) = \dot{m}_{wf} \times (h_3 - h_2)$……...(1)

For the turbine:

$\dot{W}_{turbine} = \dot{m}_{wf} \times (h_3 - h_4) \times \eta_{turbine} \times \eta_{generator}$……….(2)

For the pump:

$\dot{W}_{pump} = \dot{m}_{wf} \times v_1 \times (P_2 - P_1) / \eta_{pump}$ ....(3)

Net power output:

$\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{pump}$…..(4)

3.2.2 Efficiency Calculations

Thermal efficiency:

$\eta_{thermal} = \dot{W}_{net} / \dot{Q}_{in}$………(5)

Exergy efficiency:

$\eta_{exergy} = \dot{W}_{net} / Ex_{geo}$ …..(6)

where $Ex_{geo} = \dot{Q}_{in} \times (1 - T_0/T_{geo})$ ………………..(7)

3.3 Working Fluid Selection

R245fa (1,1,1,3,3-Pentafluoropropane) was selected as the working fluid based on the following criteria [12], [18]:

- Critical temperature of 154.01 °C, suitable for geothermal temperatures of 100–180 °C.
- Zero ozone depletion potential (ODP = 0).
- Moderate global warming potential (GWP = 1030).
- Good thermal stability and compatibility with system materials.
- Widely used in commercial Organic Rankine Cycle (ORC) systems with proven reliability.
- Favorable thermodynamic performance for low-temperature applications.

Although R245fa exhibits favorable thermodynamic properties, its moderate global warming potential (GWP = 1030) represents an environmental limitation. Alternative working fluids such as R1233zd(E) (GWP = 0.1) or natural hydrocarbons such as propane (GWP = 3) may offer improved environmental performance and could be considered in future system designs. In addition, zeotropic mixtures may enhance temperature matching within the evaporator, thereby improving cycle efficiency [20], [24].

3.4 Design Parameters and Assumptions

Table 1. Key Design Parameters and Assumptions for the Binary Cycle Geothermal Power Plant Simulation

Parameter	Value	Unit
Geothermal fluid mass flow rate	50	kg/s
Geothermal fluid temperature range	100-180	°C
Geothermal fluid pressure	1500	kPa
Ambient temperature	35	°C
Pump isentropic efficiency	85	%
Turbine isentropic efficiency	85	%
Generator efficiency	95	%
Pinch point temperature difference	10	K
Pressure ratio	5	-

3.5 MATLAB Simulation Framework

A comprehensive MATLAB-based model was developed to simulate the performance of the binary-cycle system. The simulation workflow consists of the following steps:

1. Definition of geothermal resource parameters and ambient conditions.
2. Specification of working fluid properties and system design parameters.
3. Determination of thermodynamic state points for each component.
4. Execution of energy and mass balance calculations.
5. Evaluation of performance metrics, including power output, efficiency, and specific work.
6. Economic assessment, including capital costs and levelized cost of electricity (LCOE).
7. Sensitivity analysis of key operating parameters.
8. Generation of performance curves and graphical visualization of results.

3.6 Economic Analysis Methodology

The economic feasibility of the system was evaluated using the following assumptions:

- Specific capital cost: 2,500 $/kW installed capacity
- Operation and maintenance (O&M): 2% of capital cost per annum
- Discount rate: 8%
- Plant lifetime: 25 years
- Capacity factor: 90%

Where:

- CAPEX = total capital expenditure ($)
- CRF = capital recovery factor

- r = discount rate
- n = plant lifetime (years)

Table 2. System Performance at Various Geothermal Temperatures

Temperature (°C)	Net Power (kW)	Thermal Efficiency (%)	Exergy Efficiency (%)	Specific Work (kW/kg/s)
100	1,802.6	20.29	116.50	36.05
120	3,455.8	27.79	128.53	69.12
140	5,489.9	34.34	135.10	109.80
160	7,836.8	40.10	138.97	156.74
180	10,444.0	45.22	141.33	208.88

The levelized cost of electricity (LCOE) is calculated using the capital recovery factor method:

LCOE = (CAPEX × CRF + Annual O&M) / Annual Energy Production

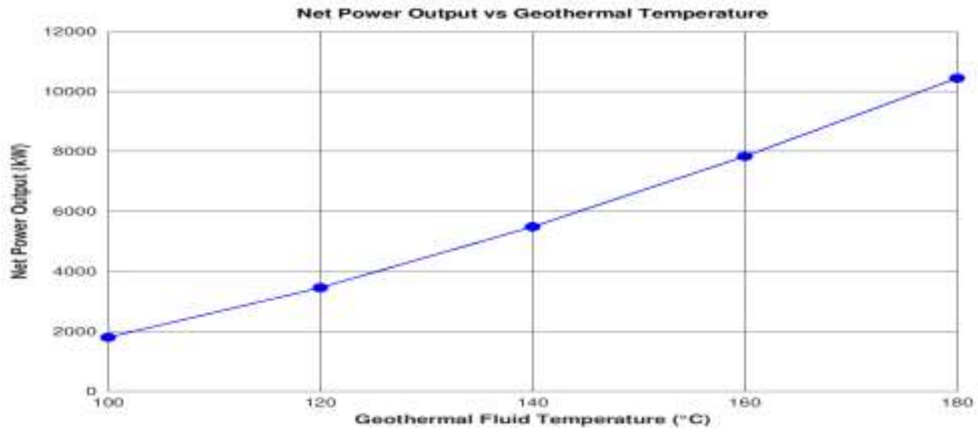
where CRF is the capital recovery factor defined as:

$CRF = r(1+r)^n / [(1+r)^n - 1]$

4. Results and Discussion

4.1 Simulation Results

Table 2: System Performance at Various Geothermal Temperatures



4.2 Power Output Analysis

Figure 2 illustrates the relationship between geothermal fluid temperature and net power output. The results indicate a strong positive correlation, with power output increasing non-linearly with temperature. The system generates 1.80 MW at 100 °C and 10.44 MW at 180 °C. This more-than-five-fold increase in power output over the investigated temperature range highlights the strong dependence of binary-cycle performance on geothermal resource temperature.

Figure 2: Net power output as a function of geothermal fluid temperature

Several factors contribute to this nonlinear relationship [3]. Higher geothermal fluid temperatures increase the temperature difference across the heat exchanger, thereby enhancing the rate of thermal energy transfer [4]. In addition, elevated temperatures enable operation at higher working fluid pressures, which improves turbine performance and increases specific work output [9].

4.3 Efficiency Analysis

Thermal and exergy efficiencies as functions of geothermal fluid temperature are presented in Figure 3. Thermal efficiency increases from 20.3% to 45.2% as the temperature rises from 100 °C to 180 °C, reflecting the thermodynamic advantage of higher-temperature heat sources. These results are consistent with reported values for binary-cycle systems operating with similar working fluids [1], [2], [19].

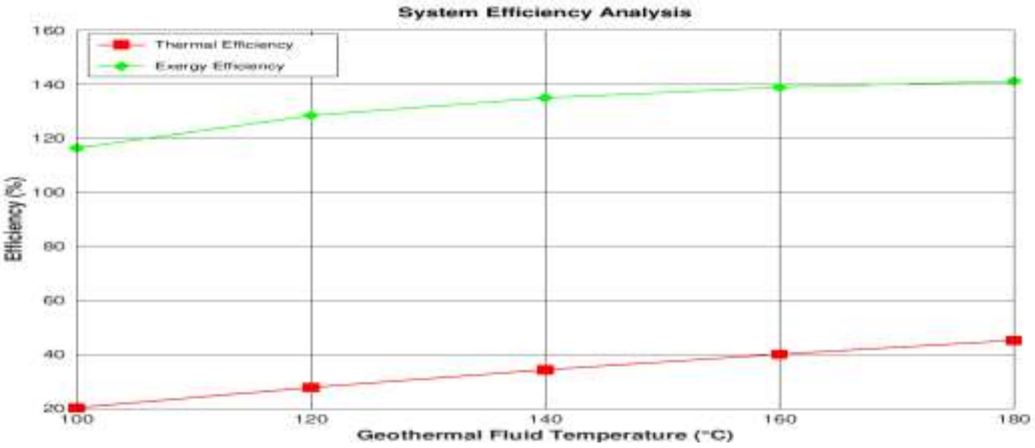


Figure 3: Thermal and exergy efficiency as functions of geothermal temperature

4.4 Specific Work Output

Specific work output per unit mass flow rate of geothermal fluid is presented in Figure 4. This metric is particularly useful for evaluating resource utilization efficiency. Specific work increases from 36.05 kW/kg/s at 100 °C to 208.88 kW/kg/s at 180 °C, indicating that higher-temperature resources can generate substantially more electricity per unit mass flow rate of extracted geothermal fluid [4], [9].

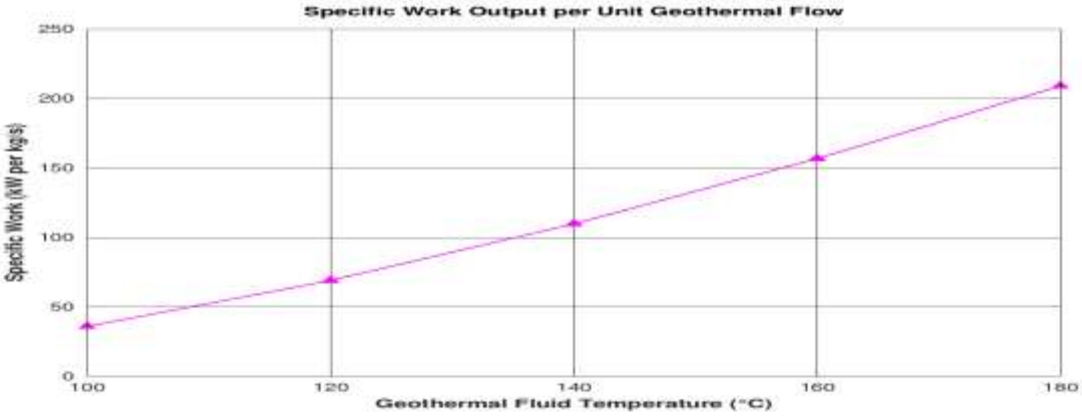


Figure 4: Specific work output per unit geothermal fluid mass flow rate

Figure 4. Specific work output per unit geothermal fluid mass flow rate

This result has important implications for wellfield development. Fewer production wells are required to achieve the same power output when higher-temperature resources are available, thereby reducing capital costs and environmental impact. For Waw an-Namus, deeper drilling to access higher-temperature reservoirs may therefore be more economically viable [21], [22].

4.5 Heat Input Requirements

Figure 5 illustrates the variation of heat input required by the ORC system with geothermal temperature. Heat input increases with temperature, from approximately 8.9 MW at 100 °C to 23.1 MW at 180 °C. This increase corresponds to higher working fluid mass flow rates and greater enthalpy rise during the evaporation process at elevated temperatures [3], [4].

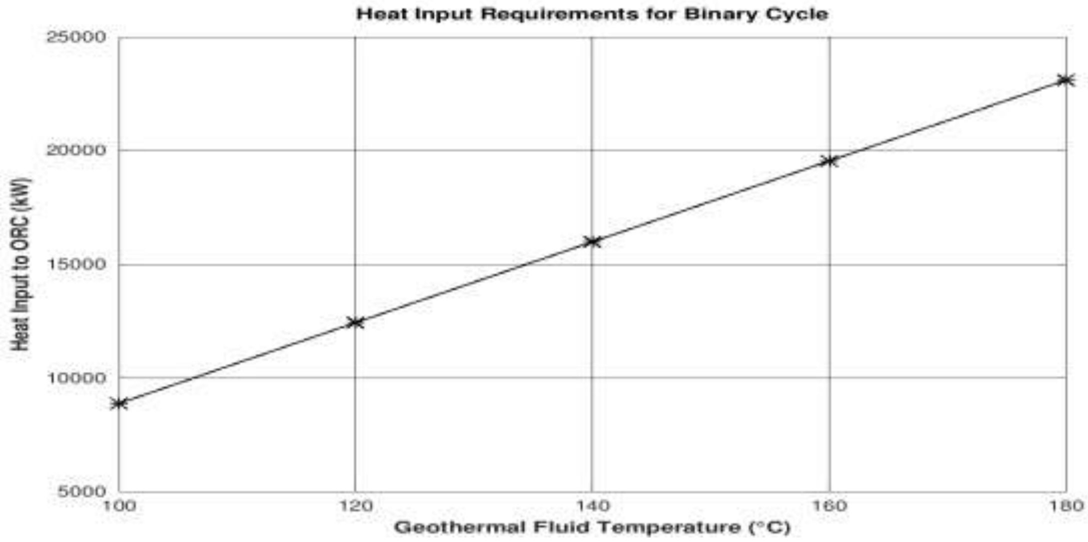


Figure 5. Heat input requirements for the binary cycle

4.6 Thermodynamic Cycle Representation

Figure 6 presents a simplified Temperature–Entropy (T–s) diagram of the ORC at a geothermal temperature of 140 °C. The four principal thermodynamic processes [1], [2] are illustrated as follows:

1. Process 1–2: Pump compression, assumed to be isentropic (approximately vertical line).
2. Process 2–3: Isobaric heat addition in the evaporator, resulting in an increase in temperature and entropy.
3. Process 3–4: Isentropic expansion in the turbine, with a reduction in temperature and entropy.
4. Process 4–1: Isobaric heat rejection in the condenser, resulting in temperature reduction.

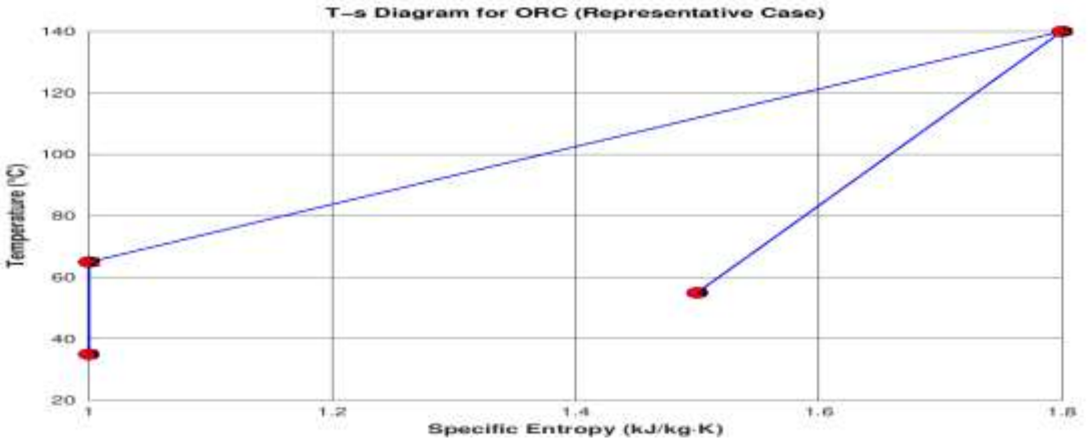


Figure 6: Temperature-Entropy diagram for the ORC (representative case at 140°C)

4.7 Sensitivity Analysis

Figure 7 presents the results of the sensitivity analysis examining the effect of pressure ratio on specific network output. The optimal pressure ratio is found to lie between 5 and 6, yielding a specific work output of approximately 110 kJ/kg [1], [3].

Operation at lower pressure ratios results in underutilization of available thermal energy, whereas excessively high-pressure ratios increase pump work disproportionately relative to turbine output [4], [9].

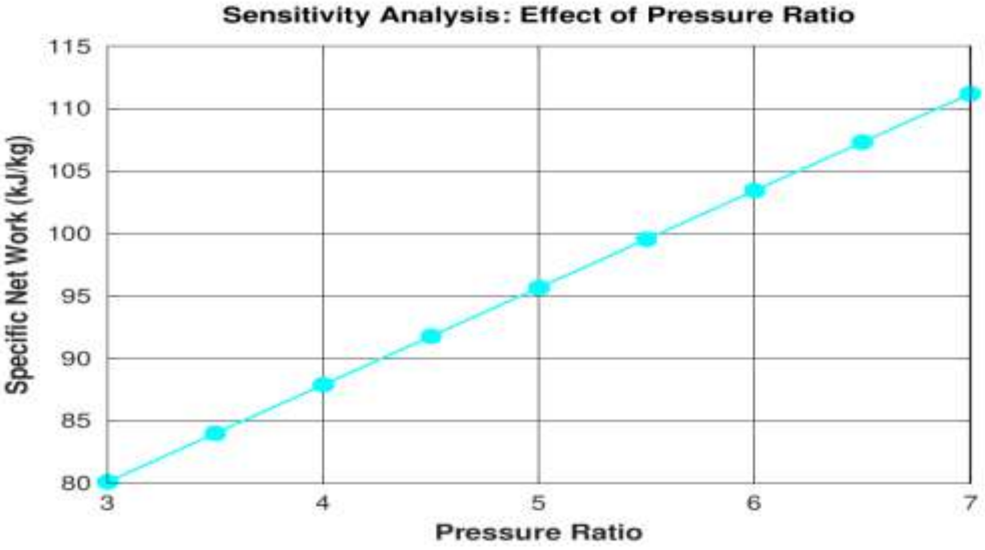


Figure 7: Effect of pressure ratio on specific network output

4.8 Economic Analysis Results

The economic analysis yielded the following average performance results across the investigated temperature range:

- Average power output: 5,805.8 kW (≈5.8 MW)
- Capital cost: $14.51 million
- Annual O&M cost: $290,000
- Annual energy production: 45,773 MWh
- Levelized cost of electricity (LCOE): $0.036/kWh

The obtained LCOE of $0.036/kWh is highly competitive with conventional power generation in Libya and other renewable energy technologies [14]. This value is lower than typical diesel generation costs (approximately $0.20–0.40/kWh in remote areas) and comparable to natural gas combined cycle plants (approximately $0.04–0.06/kWh) [25].

The economic attractiveness of the system is attributed to:

1. High-capacity factor (90%), ensuring stable energy production.
2. Absence of fuel costs, as geothermal heat is essentially free.
3. Low operation and maintenance requirements.
4. Long plant lifetime (25+ years), which allows capital cost amortization [5], [15].

4.9 Comparison with Literature

The simulation results are consistent with existing literature on binary-cycle geothermal power plants [1], [2]. The findings align with Franco and Villani (2009), who reported thermal efficiencies between 18% and 35% for ORC systems operating at geothermal temperatures of 100–160 °C.

The specific work outputs obtained for R245fa-based systems are also consistent with values reported by DiPippo (2004), supporting the validity of the thermodynamic model [2].

The economic results similarly compare well with real project data [5], [15]. Small-scale binary plants in the United States and Europe have reported LCOE values ranging from \$0.04 to \$0.08/kWh, placing the calculated value of \$0.036/kWh for Waw an-Namus in a favorable position, particularly considering potential economies of scale in Libya's renewable energy sector [17].

5. Environmental and Social Considerations

5.1 Environmental Benefits

Geothermal power generation at Waw an-Namus would provide several environmental benefits [5], [16]:

1. Greenhouse gas reduction: Substituting fossil-fuel-based generation could reduce CO_2 emissions by approximately 25,000–30,000 tonnes per year (based on displacement of diesel or heavy fuel oil generation).
2. Low land footprint: Geothermal plants require a relatively small area (2–8 m^2/MW) compared with solar (40–100 m^2/MW) or wind (100–500 m^2/MW).
3. Zero direct emissions: Binary-cycle systems operate as closed-loop systems with no direct atmospheric emissions.
4. Water conservation: Air-cooled condensers can be used in arid environments, eliminating the need for significant water consumption.
5. Reduced visual impact: Low-profile infrastructure minimizes landscape disturbance.

5.2 Sustainable Resource Management

Long-term sustainability requires effective reservoir management strategies:

1. Reinjection strategy: All extracted geothermal fluid must be reinjected to maintain reservoir pressure and minimize induced seismicity.
2. Monitoring program: Continuous monitoring of production rates, reservoir pressure, and temperature is required.
3. Adaptive management: Production rates should be adjusted in response to reservoir behavior to ensure sustainable long-term operation [5].

5.3 Social and Economic Development

Geothermal development at Waw an-Namus could generate significant socioeconomic benefits [14], [25]:

- Energy access: Provision of sustainable electricity to remote communities in southern Libya.
- Economic development: Enabling agricultural, industrial, and commercial activities.
- Employment creation: Direct jobs in construction, operation, and maintenance phases.
- Capacity building: Development of expertise in renewable energy technologies.
- Energy security: Diversification of energy sources and reduced dependence on imported fuels.

The project aligns with Libya's National Renewable Energy Strategy 2030, which aims to diversify the energy mix and reduce dependence on fossil fuels [25]. It is also consistent with the objectives of the Paris Agreement by contributing low-carbon baseload electricity in a climate-vulnerable region [14].

6. Challenges and Recommendations

6.1 Technical Challenges

Several technical challenges must be addressed to ensure successful implementation of the project:

1. Resource confirmation: Detailed exploration using geophysical surveys, gradient drilling, and resource testing is required.
2. Fluid chemistry: High salinity or corrosive constituents may be present, requiring specialized materials and corrosion control systems.
3. Scaling and corrosion: Appropriate mitigation strategies for chemical precipitation, scaling, and corrosion must be implemented.
4. Remote location: Transportation and maintenance logistics are challenging due to the remote desert environment.
5. Grid connection: Development of transmission infrastructure is required to connect the plant to load centers.

6.2 Institutional and Policy Recommendations

Effective geothermal development requires supportive institutional and regulatory frameworks [14], [25]:

- Regulatory framework: Establish clear guidelines for geothermal exploration and development.
- Resource rights: Define ownership and licensing structures for geothermal resources.
- Incentives: Introduce feed-in tariffs or power purchase agreements (PPAs) to encourage private investment.
- Capacity building: Develop local expertise through training and international collaboration.
- Research support: Increase investment in geothermal resource assessment and technological optimization in Libya.

These recommendations are consistent with Libya’s National Renewable Energy Strategy 2030 [25] and align with IRENA guidelines for geothermal development in North Africa [14].

6.3 Recommended Project Development Phases

A phased development approach is recommended:

Phase 1: Exploration (2–3 years)

- Geological and geophysical surveys
- Drilling of slim exploration wells (1000–3000 m depth)
- Flow and temperature gradient testing
- Reservoir characterization and resource assessment

Phase 2: Pilot Plant (2–3 years)

- Design and engineering of a 1–2 MW demonstration plant
- Drilling of production and injection wells
- Installation and procurement of ORC system
- System testing and optimization
- Performance validation

Phase 3: Commercial Development (3–5 years)

- Scale-up to 5–10 MW capacity
- Further development of the wellfield
- Construction of full-scale power plant
- Grid connection infrastructure development
- Commencement of commercial operation

7. Conclusions

This study provides technical and economic evidence supporting the feasibility of geothermal energy exploitation at Waw an-Namus, Libya, for electricity generation using binary-cycle technology. The main conclusions are summarized as follows:

1. Resource potential: Waw an-Namus exhibits significant geothermal potential, with estimated reservoir temperatures of 120–200 °C at depths of 2000–3000 m, indicating suitability for commercial development.
2. Technical viability: The R245fa-based Organic Rankine Cycle (ORC) system can efficiently convert geothermal heat into electricity. At 140 °C and a mass flow rate of 50 kg/s, the system produces approximately 5.49 MW of net power with a thermal efficiency of 34.3%.
3. Performance characteristics: System performance is strongly dependent on geothermal temperature, with power output increasing from 1.8 MW at 100 °C to 10.4 MW at 180 °C. Thermal efficiency ranges from 20% to 45%, consistent with commercial binary-cycle systems.
4. Economic competitiveness: The calculated LCOE of $0.036/kWh is highly competitive with conventional generation technologies. A 5.8 MW plant requires an estimated capital cost of $14.5 million, which is economically feasible given the maturity and long lifespan of the technology.
5. Environmental benefits: Geothermal development could offset approximately 25,000–30,000 tonnes of CO_2 emissions annually while providing reliable baseload electricity with minimal environmental impact.
6. Optimization opportunities: Sensitivity analysis indicates an optimal pressure ratio of 5–6. Further improvements using advanced cycle configurations (e.g., regenerative or dual-pressure systems) may yield efficiency gains of 5–10%.
7. Broader implications: Successful development at Waw an-Namus could serve as a reference model for geothermal projects across Libya and North Africa, contributing to regional energy security and sustainable development goals.

Future Research Directions

Future work should focus on:

1. Detailed geophysical surveys and exploratory drilling to confirm reservoir characteristics.
2. Advanced thermodynamic modeling including transient and part-load conditions.
3. Optimization of working fluids considering environmental regulations and performance trade-offs.
4. Integration of hybrid renewable systems (solar–wind–geothermal).
5. Life cycle assessment incorporating environmental and social impacts.
6. Expanded geothermal resource mapping across southern Libya.

To sum up, Geothermal energy development at Waw an-Namus represents a strategic opportunity to advance Libya’s renewable energy transition, enhance energy security, and contribute to global climate mitigation efforts. The demonstrated technical feasibility, economic attractiveness, and environmental benefits provide a strong foundation for policymakers, investors, and development agencies to consider phased implementation and further exploration.

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