

Optimization of Geothermal ORC Power Generation Technologies

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Abstract:

Grounding the analysis in thermodynamic principles, this comprehensive review systematically deciphers the efficiency constraints inherent in geothermal Organic Rankine Cycle (ORC) power generation technology. Progressing to a coupled examination of working fluid thermophysical properties and system architectural configurations, it reveals the divergent impact of environmental regulations and resource endowment on technological pathway selection. Through comparative assessment of globally representative cases (including Iceland's high-enthalpy fields, Hubei's policy-driven zones, and North China's hybrid models), the study turns out to elucidate how regional development disparities precipitate technical standard fragmentation. Conclusively, a synergistic technology-policy framework is proposed, demonstrating the integrated value of supercritical CO₂ working fluids, artificial intelligence optimization, and carbon pricing mechanisms (e.g. CBAM) in overcoming efficiency barriers. The perspective extends to ORC's evolving role within smart energy networks, projecting its transition toward baseload integration in future energy internet ecosystems. Last but not the least, this review does not involve complex theoretical analysis, system integration, or component analysis. Its purpose is to help beginners understand the underlying logic.

Keywords: Organic Rankine Cycle (ORC); Geothermal Power Generation; Exergy Efficiency; Techno-Economic Optimization.

1. Introduction

Under the "Dual Carbon" goals (carbon peaking and carbon neutrality), geothermal energy, characterized by high stability and extensive reserves as a renewable resource, has become a critical pathway for

energy transition through power generation [1, 2]. Compared to the conventional Steam Rankine Cycle (SRC), the Organic Rankine Cycle (ORC) significantly enhances the economic viability and technical feasibility of geothermal power generation, owing to its adaptability to medium-low temperature heat

sources (80 ~ 200°C) and modular deployment flexibility [3]. However, current geothermal ORC plants are facing persistent bottlenecks: Average thermal efficiency generally remains below 25%; They're constrained by the policy requirements regarding the environmental concerns over working fluids (e.g., phase-out pressure of high-Global Warming Potential (GWP) refrigerants) and insufficient system integration [4].

This review will systematically synthesize research advances in geothermal ORC technology. Beginning with a thermodynamic framework, it evaluates working fluid selection strategies and efficiency optimization pathways, analyzes global application cases to extract operational insights, and forecasts future development opportunities aligned with existing technologies and policy orientations. Rather than delving into component-level innovations or system optimization, this work provides a comprehensive technological panorama for researchers who have only recently begun exploring this field, as well as supports engineering decision-making.

2. Introduction to Thermodynamics Fundamentals and ORC Systems

2.1 Fundamental Principle

ORC achieves efficient power generation from medium-low temperature heat sources (80 ~ 200 °C) by replacing water with organic working fluids. Its thermodynamic process involves four core components.

- (1) Evaporator: Geothermal fluid heats the organic working fluid, evaporating it into high-pressure vapor (heat absorption process Q_{in}).
- (2) Turbine: High-pressure vapor drives the turbine to generate mechanical work (output work $W_{turbine}$).
- (3) Condenser: Low-pressure vapor condenses into liquid (heat rejection process Q_{out}).
- (4) Working fluid pump: Liquid working fluid is pressurized and returned to the evaporator (power consumption

W_{pump}).

2.2 Core Formulae

- (1) Thermal efficiency: Quantifies the conversion efficiency from thermal energy to mechanical work.

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{turbine} - W_{pump}}{Q_{in}} \quad (1)$$

Physical significance: For geothermal sources <150°C, ORC thermal efficiency typically ranges from 10% to 18%, significantly exceeding conventional steam cycles (<8%) [2].

- (2) Net power output: Represents the actual electricity generation capacity of the system.

$$W_{net} = W_{turbine} - W_{pump} \quad (2)$$

Note: Turbine output work must deduct pump consumption losses. Net power output in geothermal ORC plants generally ranges from 1 to 5 MW.

- (3) Exergy efficiency: Reflects the utilization rate of energy "quality".

$$\eta_{ex} = \frac{W_{net}}{E_{in}} \quad (3)$$

Where E_{in} is the input exergy of the geothermal fluid. Exergy efficiency serves as a critical sustainability indicator for geothermal systems, as only a fraction of the geothermal fluid's energy can be converted to useful work (exergy). For example, 150°C geothermal water possesses an exergy value accounting for merely 35% ~ 40% of its thermal energy. Consequently, enhancing exergy efficiency constitutes the core challenge in ORC technology. Optimized systems like Iceland's Hellisheiði plant achieve over 25% exergy efficiency [5].

2.3 Distinctive Advantages of ORC in Geothermal Applications

Compared to the conventional SRC, ORC demonstrates three significant advantages in geothermal power generation (described in table 1).

Table 1. Comparative analysis of SRC and ORC systems for geothermal applications

Feature	SRC	ORC	Advantage description
Applicable temperature	>250°C	80 ~ 200°C	Adaptation to medium and low-temperature geothermal resources (accounting for 70% of the global geothermal reserves)
Critical pressure of the working fluid	22.1MPa(water)	1 ~ 4Mpa (e.g. R245a)	Reduce the pressure-bearing requirements of the system and minimize the risk of leakage.
part load performance	Efficiency plummeted.	Slow attenuation	Accommodates fluctuations in geothermal flow, ensuring consistent power generation stability.

The following provides illustrative examples of innovations across various aspects of ORC technology.

(1) Modular design: With unit capacities ranging from 0.1 to 10 MW, ORC systems enable flexible deployment around geothermal well clusters, minimizing heat loss from pipelines.

(2) Combined Heat and Power (CHP): Utilizing waste heat from ORC exhaust for district heating elevates overall system efficiency to 60% ~ 80%, as demonstrated in the Xiong'an New Area geothermal ORC demonstration project.

(3) Smart microgrid integration: Distributed ORC units aggregated through virtual power plant (VPP) technology participate in grid peak shaving [6].

3. Selection of Working Medium and Ways to Enhance System Efficiency

3.1 Working Fluid Selection: Engineering Extension of Thermodynamic Principles

The core efficiency of ORC power generation hinges on the matching between working fluids and heat sources. As established in Section 2, ORC's thermal efficiency (η_{th}) and exergy efficiency (η_{ex}) are directly governed by fluid thermophysical properties. When geothermal sources are below 150°C, critical temperature, latent heat of vaporization, and other thermophysical properties of working

fluids govern system performance via the following key mechanisms.

(1) Critical temperature constraint: The critical temperature of the working fluid must exceed the heat sources' temperature by 20 ~ 40°C to prevent phase transition during expansion—a preventative measure against turbine liquid slugging.

(2) Latent-to-sensible heat ratio: Working fluids with high latent heat of vaporization enhance heat transfer efficiency within evaporators but impose additional thermal load on condensers.

(3) Low thermal conductivity loss: The thermal conductivity of organic working fluids is only 1/5 to 1/10 that of water, which can lead to significant heat transfer irreversibility.

The following is the verification of the key scientific issues involved.

(1) Investigation of working fluid performance in high-temperature regions: R1233zd(E) shows optimal exergy efficiency (>24.8% in the Datong project) in geothermal fields exceeding 150°C. Its critical temperature of 190°C provides an effective match for high-temperature heat sources, representing a 12.3% improvement in cycle work output compared to R245fa [7, 8].

(2) The data shown in table 2 help to make clear comparison of physical properties in the medium and low temperature zones

Table 2. Actual measurement data of the project in Xiaogan, Hubei Province [8]

Working Medium	GWP	Thermal Efficiency (%)	Main Cause of Efficiency Loss
R245fa	1030	22.7	High global warming potential
R1234ze	6	14.8	Low latent heat of evaporation(147 kJ/kg)

(3) Consideration of safety-economic boundary conditions: Hydrocarbon working fluids such as propane (R290) can reduce system costs by 35%. However, due to their flammability, they must comply with the safety regulation requiring "Installation Spacing $\geq 0.2 \times$ system power (MW)" (ASME B31.3). In contrast, the zeotropic mixture R245fa/R1234ze (0.7:0.3) achieves an 8.2% improvement in thermal efficiency while maintaining a GWP < 150. This validates the concept that "composition regulation can overcome physical property performance limits" [8]. Due to the increasing complexity of multivariate nonlinear relationships between working fluid properties and system efficiency, artificial intelligence (AI) methods have demonstrated their capability for high-fidelity modeling of the thermo-economic coupling mechanisms in geothermal ORC systems. This provides robust support for next-generation tools in working fluid screening and operational

optimization [9].

3.2 System Efficiency Enhancement: The Engineering Costs of Architectural Innovation

The properties of working fluids determine the applicability boundaries of efficiency-boosting technologies. Current mainstream technologies enhance exergy utilization through thermodynamic cycle innovations, but vigilance is required because hidden costs increase when performance gains.

(1) Recuperative Technology: The highest return on investment is achieved when preheating the liquid working fluid with waste exhaust heat. An R245fa system can increase net power output by 5-10% while incurring only a <5% increase in cost. However, its effectiveness relies heavily on fluid superheat levels and proves being ineffective for high-pressure fluids like R1233zd(E) [7, 10].

(2) Regenerative & Reheating Technologies: Although it can increase efficiency by 15 ~ 24%, the cost is extremely high. The regenerative ORC system in the Datong project has an energy efficiency of 19.3%, but it leads to a 12% increase in compressor failure rate and a 18% increase in cost; while the R1233zd(E)+ reheating architecture requires custom turbine equipment, resulting in an initial investment increase of 30%. [8, 11].

(3) Multi-energy Synergy: Examples like geothermal-natural gas hybrid plants utilize gas turbine waste heat to drive ORC, boosting overall efficiency to 60 ~ 80%. Yet, control complexity limits their application in small-scale power plants (only economically viable above 10MW).

We can reasonably infer that the key breakthrough point in the future lies in the integrated design of working medium and architecture. In current experiments being conducted in Jiangsu, the supercritical CO₂-water miscible working medium (95:5) demonstrated considerable potential, and its compact turbine structure can reduce the mechanical complexity of the regeneration cycle. This undoubtedly provides compelling support for the validity of our hypothesized solution.

4. Current Global Application Status of Geothermal ORC Power Generation

4.1 The Three-dimensional Driving Model of Technology Diffusion

As discussed in Section 3, working fluid selection and system architecture collectively define the techno-economic threshold, which in turn determines the extent of ORC applicability across different regions. The global deployment of geothermal ORC systems represents a dynamic interplay among resource endowment, technological compatibility, and policy incentives. This interplay will be analyzed through three case studies in the following section.

(1) Resource-Dominant Model (Iceland): Volcanic activity endows this region with 180 ~ 250°C high-temperature resources, allowing ORC plants to implement high-efficiency single-stage cycles while obviating cost-prohibitive recuperative systems. Despite historical reliance on non-compliant R245fa (GWP=1030), exceptionally low wellhead development costs (at 40% below the global average) enabled absorption of the incremental investment required for transitioning to R1233zd(E) by 2023, which at last made the ORC plants to achieve a local electricity proportion of 90% legally and in compliance with regulations [12]. This proves that high-quality geothermal resources can transcend policy barriers to drive technological development.

(2) Policy-Driven Model (Hubei, China): Medium-low temperature resources (90 ~ 130°C) inherently constrain thermal efficiency (<12%), yet Hubei's Zero-Carbon Park policy bridges the economic gap through feed-in tariffs and carbon credit trading. Exemplified by the Xiaogan project employing R1234ze (GWP=6) with photovoltaic hybridization, although generation costs reach 2.1 times those of conventional hydropower—but policy incentives secure an “8-year payback period”, demonstrating administrative intervention's capacity to rectify market failures [13].

(3) Hybrid Model (North China): Leveraging Sinopec's geothermal development infrastructure in the Xiong'an New Area, this model integrates medium-temperature resources (110 ~ 150°C) with economies of scale to develop integrated cogeneration systems for combined ORC power generation and district heating. While its working fluid selection (R245fa) lags behind environmental trends, modular replication strategies reduce unit capital costs to \$2,800/kW, validating how scaled deployment fosters technological maturity [14].

These case studies could help us find out that resource-dominant regions prioritize efficiency gains over policy compliance, policy-driven zones accelerate deployment through administrative intervention at the expense of technological evolution, and hybrid models exhibit delayed working fluid innovation due to path dependency. While diverse regions implement localized approaches, this uncoordinated fragmentation inevitably leads to a globally fragmented ORC knowledge base, thereby substantially hindering technological standardization progress.

4.2 China's Evolving Role in Geothermal ORC Development

Despite regionally fragmented global ORC deployment, China's geothermal sector has advanced adaptive innovations for complex scenarios. A representative case is the world's first ISO 9160-compliant working fluid performance database established at Nanjing's megawatt-scale ORC test platform (2023). This initiative reduced international costs for fluids like R1233zd(E) by 24%, progressively disrupting entrenched technological monopolies [13], signaling a transition from technology adoption toward active engagement in international standardization. However, while diverse global implementations expand the technological boundaries of ORC systems, they simultaneously highlight systemic deficiencies—namely, lagging efficiency evolution and the absence of integrated standards. The sustainability of current technological pathes will face severe challenges when confronted with

weakened policy support (e.g. adjustment to the EU carbon tax) or declining resource quality (e.g. 0.5°C annual temperature drop in some Icelandic wells).

5. Technical Challenges and Development Trends

5.1 Efficiency bottlenecks and cost constraints

The fundamental challenge in current geothermal ORC power generation lies in the structural conflict between stagnant thermal efficiency and cost-reduction imperatives. Exergy destruction imbalance constitutes the primary constraint—evaporators and condensers contribute 72 ~ 85% of total system exergy loss. This phenomenon primarily stems from irreversible losses caused by above 40 °C heat transfer differentials between geothermal fluids and working fluids, coupled with suboptimal thermal conductivity of organic working fluids. This effect is particularly significant in medium and low-temperature scenarios (<150°C), and a substantial amount of field measurement data suggests that the attenuation of the net output power can range from 25% to 30%.

Simultaneously, the transference of environmental costs exacerbates economic challenges. While low-GWP fluids like R1233zd(E) align with regulatory trends, their high-pressure characteristics necessitate custom titanium alloy heat exchangers, which results in increasing unit capital costs by 35% compared to conventional systems. Such environmental premiums extend payback periods beyond 12 years in unsubsidized markets, substantially constraining technology penetration rates.

5.2 Policy-driven technological leapfrogging path

The root cause of efficiency bottlenecks lies in the misalignment between technological iteration cycles and policy regulatory rhythms. Mechanisms like the EU's Carbon Border Adjustment Mechanism (CBAM) are compelling resource-rich nations (e.g. Indonesia, Kenya) to phase out high-GWP working fluids, thereby compelling technological upgrades. Therefore, future breakthroughs may advance along these three strategic dimensions below.

- (1) sCO₂—based thermal management: Enabling dual-functionality as heat-transfer medium and thermochemical storage (e.g. PV—geothermal hybridization).
- (2) AI-driven operational optimization: Deriving efficiency pathways from multi-million scenario datasets.
- (3) Carbon credit monetization: Establishing green certificate chains to unlock carbon credit revenues.

6. Conclusion

This review systematically discusses about geothermal ORC power generation, elucidating three fundamental patterns.

- (1) The thermodynamic performance of such systems is constrained by exergy destruction.
- (2) The evolutionary pathway will be co-created by resources and policy frameworks.
- (3) Breakthroughs in efficiency necessitate concerted efforts across technological innovation and policy support mechanisms.

In the foreseeable future, solar-geothermal synergy and the emerging global green certificate trading network are poised to accelerate ORC commercialization, enabling its progression from an ancillary role to baseload power generation.

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