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Role of Geothermal Energy in Sustainable Development

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Abstract

Rising global energy demand and the environmental consequences of fossil fuel combustion have pushed the transition to clean renewable sources. Geothermal energy could work as viable alternative to fossil fuel as it provides energy by heat extracted from the Earth's interior. Unlike solar and wind energy, geothermal energy systems provide a continuous baseload power supply unaffected by weather conditions. We have analysed major geothermal conversion systems such as conventional flash steam/dry steam systems and the Organic Rankine Cycle (ORC) low-boiling-point closed-loop system. This paper examines the role of geothermal energy in sustainable development through the lens of global statistics, environmental CO_2 data, economic impact, and policy dimensions.

Keywords: Geothermal energy, Organic Rankine Cycle, ORC, binary cycle, flash steam, sustainable development, CO_2 emissions, renewable energy, baseload power, closed-loop system

1. Introduction

Energy is the cornerstone of modern civilization, from industrial production to transportation, agriculture, healthcare, and domestic usage. For over a century, the global energy system has been dominated by fossil fuels such as coal, oil, and natural gas which together contributed approximately 81% of total primary energy supply as of 2017, according to the International Energy Agency (IEA). The burning of coal, oil, and natural gas released approximately 33.1 Gt of CO_2 in 2018 alone pushing global average temperatures steadily toward dangerous thresholds.

Among the renewable alternatives, geothermal energy occupies a uniquely important position. It harnesses thermal energy stored within the Earth's crust produced by radioactive isotope decay and residual planetary heat and convert this thermal energy in electricity and direct running heat. Unlike solar or wind, geothermal systems operate continuously, day and night, regardless of weather conditions, achieving average capacity factors of 80–95% which provides stable energy generation that could help with maintaining grids. (IRENA, 2017).

Two principal technological pathways exist for converting geothermal heat into electricity:

1) Conventional flash steam and dry steam systems that exploit high-temperature hydrothermal resources.

(2) the Organic Rankine Cycle (ORC) binary system, which utilises a low-boiling-point working fluid in a fully closed loop to exploit lower-temperature resources.

2. Literature Review

The academic literature has continuously shown geothermal energy's potential as a sustainable energy system. Fridleifsson et al. (2008) established that geothermal resources have the theoretical capacity to meet a significant share of global baseload electricity needs, especially in tectonically active zones where the geothermal heat is closer to surface and higher in magnitude. In a report by the Geothermal Energy Association (2015), installed global capacity of geothermal energy production had increased from 10.9 gigawatts (GW) in 2010 to 12.8 GW in 2015, with new large-scale development of geothermal power plants in Turkey, Indonesia, and Kenya as the primary drivers of this growth

IRENA (2017) reported that global geothermal generation had reached 80 TWh by 2016 and projected expansion to 200 GW by 2030 due to continuous renewable energy expansion. Bertani (2016) provided the most comprehensive global survey to that date, cataloguing installed capacity across all producing nations and documenting the rapid rise of binary cycle technology for lower-temperature resources.

Lund and Boyd (2016) reported that the total world capacity for direct use of geothermal energy was 107,727 megawatts thermal (MWt) in 2015, with all possible applications ranging from domestic and commercial space heating to industrial processes. On the environmental side, Tomasini-Montenegro et al. (2017) identified the lifecycle emissions for flash steam geothermal power generation to be in the range of 15 to 55 grams of CO2 equivalent/kWh and for binary cycle generation to be near zero. However, existing literature has also highlighted several challenges such as high upfront drilling costs, geographic limitations and increase in seismic activity risks associated with Enhanced Geothermal Systems (EGS).

3. Methodology

Research Design

This study applies a qualitative and review-based research design. It relies on secondary data from international energy reports, governmental publications, peer-reviewed journals, and institutional databases.

Data Sources

- IRENA Renewable Capacity Statistics & Technology Briefs (2015–2019)
- IEA World Energy Outlook Reports (2017–2019)
- REN21 Global Status Reports (2017–2019)
- Geothermal Energy Association (GEA) Annual Reports (2015–2019)
- IPCC Fifth Assessment Report (2014) & SR1.5 (2018)

- DiPippo (2012) — Geothermal Power Plants (3rd ed.)
- Walraven et al. (2013) — ORC working fluid optimisation

Data Analysis Method

The analysis consists of descriptive and trend-based methods such as global installed capacity (GW), generation (TWh), lifecycle GHG emissions (g CO_2eq/kWh), capacity factors, LCOE values (USD/kWh), employment figures, and thermodynamic performance parameters of both conventional and ORC geothermal systems.

4. Conventional Flash Steam Geothermal System

A. Operating Principle

Conventional geothermal power plants exploit high-temperature hydrothermal reservoirs where pressurised fluid exceeds 182°C. In a flash steam plant, high-pressure brine is brought to the surface through production wells and allowed to "flash" — rapidly depressurise — inside a separator vessel, converting a portion into dry steam. This steam expands through a turbine to generate mechanical shaft work, which is converted to electricity by the generator. Exhaust steam is condensed and, together with residual brine from the separator, returned to the reservoir via re-injection wells. Dry steam plants — used at The Geysers (California, 1,520 MW) — are a simpler variant where superheated steam exits the well directly (DiPippo, 2012).

B. Key Components

The principal components are: production well, wellhead valve, centrifugal flash separator, steam turbine, electrical generator, step-up transformer, condenser, cooling tower, brine re-injection pump, and re-injection well. Flash steam systems account for ~62% of global geothermal installed capacity as of 2018 (Bertani, 2016).

Table 1: Components of Conventional Flash Steam Geothermal System

Component	Function	Operating Condition
Production Well	**Extracts hot brine from reservoir**	**>182°C, high pressure**
Flash Separator	**Converts pressurised brine to steam + liquid**	**Pressure drop ~5 bar**
Steam Turbine	**Converts steam enthalpy to shaft work**	**Saturated/superheated steam**
Generator	**Converts shaft work to AC electricity**	**50/60 Hz output**

Condenser	**Condenses exhaust steam to liquid**	**Vacuum ~0.1 bar**
Cooling Tower	**Rejects waste heat to atmosphere**	**Wet or dry cooling**
Re-injection Pump	**Returns spent fluid under pressure**	**High-pressure injection**
Re-injection Well	**Maintains reservoir pressure**	**1–3 km deep borehole**

Source: DiPippo (2012); GEA (2019)

5. ORC Low-Boiling-Point Closed-Loop System

A. Operating Principle

The Organic Rankine Cycle (ORC) Binary is designed for low and medium temperature geothermal resources (70°C to 180°C), through the use of geothermal brine to heat an Organic Working Fluid with a Boiling Point significantly below Water, via a heat exchanger (evaporator). The Organic Vapour then expands through an ORC turbine, generating electricity via a generator, before cycling back to liquid via a condenser. The liquid is then re-pressurised by a feed pump to return to the evaporator through a completely closed loop. The geothermal brine does not come into contact with the atmosphere, and is fully re-injected into the geothermal reservoir (Walraven et al. 2013).

B. Working Fluids

The most common working fluids for ORC systems are Isobutane (Boiling Point -11.7°C), Isopentane (Boiling Point 27.7°C), n-Pentane (Boiling Point 36.1) and R-134a (F-gas)(Boiling Point -26.3°C); all of these fluids were selected based on the temperature of the resource, the target efficiency of the cycle, the environmental impact, and safety. The average thermal efficiency of ORC systems between 120°C and 150°C is 10% to 15% (Walraven et al., 2013). Due to the closed loop system, ORC facilities have virtually no atmospheric emissions - No CO2, No H2S, and as such, Binary ORC plants have an average lifecycle emission of less than 4 g CO2eq/kWh (IPCC, 2014).

Table 2: Components of the ORC Binary Closed-Loop Geothermal System

Component	**Function**	**Detail**
Production Well	**Extracts low-to-medium temp. brine**	**70–180°C resource**
Heat Exchanger (Evaporator)	**Transfers heat: brine → ORC fluid**	**Shell-and-tube / plate type**

ORC Working Fluid	**Low boiling-point heat carrier**	**Isobutane, isopentane, R-134a**
ORC Turbine (Expander)	**Expands ORC vapour → shaft work**	**Radial or axial turbine**
Generator	**Converts shaft work to AC electricity**	**50/60 Hz output**
Condenser	**Cools ORC vapour → liquid**	**Air-cooled or water-cooled**
Feed Pump	**Re-pressurises liquid ORC fluid**	**Closes the ORC loop**
Re-injection Pump	**Returns cooled brine to reservoir**	**100% brine re-injection**
Re-injection Well	**Maintains reservoir sustainability**	**1–3 km deep borehole**

Source: DiPippo (2012); Walraven et al. (2013); IRENA (2017)

6. Data Analysis

Table 3: Conventional Flash Steam vs. ORC Binary — Key Parameters

Parameter	Flash Steam	ORC Binary
Resource Temp.	**>182°C**	**70–180°C**
Working Fluid	**Geothermal steam**	**Organic (isobutane etc.)**
Atmospheric Emissions	**CO_2, H_2S possible**	**~Zero (sealed loop)**
CO_2 Lifecycle (g/kWh)	**15–55**	**~4**
Cycle Efficiency	**10–23%**	**10–15%**
Capacity Factor	**80–95%**	**80–95%**
Geographic Reach	**Volcanic/tectonic zones**	**Much wider (low-temp zones)**

Brine Re-injection	**Partial**	**100% mandatory**
Water Consumption	**0.15 L/kWh**	**~0 L/kWh**
Global Share (2018)	**~62% of capacity**	**~38% of plant count**
LCOE Range (USD/kWh)	**0.04–0.10**	**0.07–0.14**

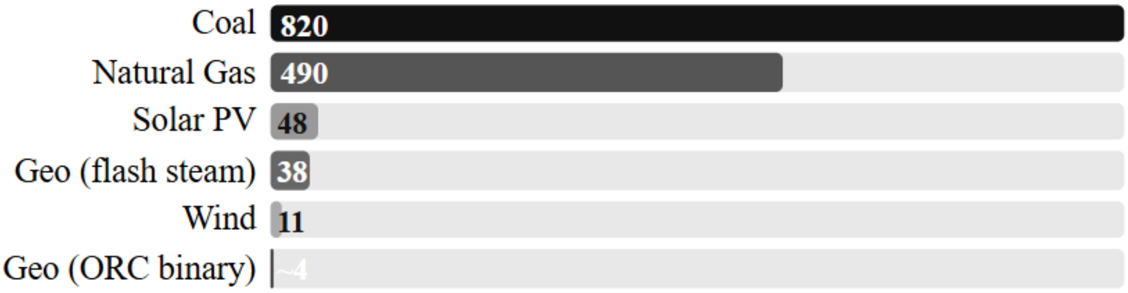
Source: DiPippo (2012); IRENA (2017); Bertani (2016); IPCC (2014)

Table 4: Global Geothermal Capacity & Generation (2010–2018)

Year	Capacity (GW)	Generation (TWh)	Countries
2010	**10.9**	**67.2**	**24**
2013	**11.8**	**72.0**	**26**
2015	**12.8**	**78.0**	**28**
2017	**13.2**	**86.0**	**29**
2018	**13.3**	**90.2**	**29**

Source: IRENA (2019); Bertani (2016)

Figure 5: Lifecycle CO$_2$eq Emissions Comparison (g CO$_2$eq/kWh)



Source: IPCC (2014); IRENA (2017); Tomasini-Montenegro et al. (2017)

7. Environmental Impact

Geothermal energy is considered one of the most carbon-neutral methods of producing electricity. A typical flash steam generation facility generally emits between 15 and 55 g CO2eq/kWh of greenhouse gases over its entire lifecycle; this is a small amount compared to coal (~820 g CO2eq/kWh) and natural gas (approximately 490 g CO2eq/kWh), and supports the Paris Agreement Climate Change Mitigation Objectives. Geothermal power generation generally requires a smaller land footprint (in comparison with solar and wind) and does not combust fuel, thereby greatly minimizing any potential habitat disruption. Additionally, binary cycle geothermal power generation is essentially zero emission when generating power from geothermal resources due to its closed-loop operation. Sustainability is further improved through the reinjection of the geothermal resource into the reservoir. This practice is common in Iceland and some parts of the U.S. and helps maintain reservoir pressure, prevents surface contamination from the surface, and allows the geothermal resource to be utilized over a long period of time.

8. Economic & Social Impact

Table 5: LCOE Comparison by Technology (2017, USD/kWh)

Technology	Avg. LCOE	Range
Coal (new plant)	**0.102**	**0.066–0.152**
Natural Gas (CCGT)	**0.091**	**0.049–0.174**
Solar PV (utility)	**0.100**	**0.049–0.389**
Wind (onshore)	**0.060**	**0.045–0.102**
Geothermal (all)	**0.070**	**0.040–0.140**

Source: IRENA Renewable Power Generation Costs (2018)

Geothermal power generation has a positive impact on the socio-economic environment of an area due to the amount of money that can be gained by using geothermal energy. In Iceland, the cost of home heating has dropped by almost 50% compared to oil-based home heating systems due to the use of geothermal energy by 2019. This has improved the quality of life for households as well as increasing the global competitiveness of Iceland. There were approximately 150,000 jobs related to the global geothermal industry in 2018 according to IRENA (International Renewable Energy Agency). In Kenya, the increase in the availability of electricity from geothermal energy has decreased electricity tariffs for households by over 30% from 2014 to 2019, indicating the role that geothermal energy plays in energy security and poverty alleviation (World Bank 2019).

Geothermal power plants that produce electricity between 1MW and 5MW are an excellent source of electricity in remote communities as baseload power sources, thus reducing the use of fossil fuel-based energy sources and decreasing the risk of fluctuating fuel prices. The use of geothermal energy in food production is also being explored in places such as Iceland, China, and the United States through geothermal greenhouse heating, where yields of crops can increase by 30-60% when growing in cold climates, which supports the attainment of Sustainable Development Goal #2 regarding improved food security.

9. Challenges

The deployment of geothermal energy, while promising, faces many structural, financial, and regulatory barriers.

High Upfront Capital Risk-The death toll on exploration and development wells is extremely high and ranges from $2 million to $5 million. The average number of wells necessary before making any commercial commitment is between three and eight wells. This very capital-intensive, high-risk exploration phase discourages private capital from investing, particularly in developing world countries without risk mitigation instruments.

Geographic Limitations. High-temperature geothermal resources that are suitable for power generation are concentrated in regions of tectonic activity, including the Pacific "Ring of Fire," the East African Rift Valley, and the Mid-Atlantic Ridge. In the majority of countries outside these regions, low enthalpy geothermal resources are predominately utilized for lower-temperature applications, or Organic Rankine Cycle (ORC) Technologies, which may allow for greater geographic distribution but also typically require higher levelized cost of electricity (LCOE).

Long Development Timeframes-Generally, from the time of exploration to when the actual project can be constructed and put into operation, the typical time required for a geothermal project is 7–10 years. For comparison, the time required for wind or solar projects is 1–3 years. A longer development timeframe equates to more financing costs and more uncertainty to an investor.

Risks of Induced Seismicity-In recent years, as Enhanced Geothermal Systems (EGS) have been developed utilizing hydraulic stimulation methods, minor to moderate seismic activity has occurred. Cases include the Basel (Basel M3.4) EGS project in 2006 and the recent Pohang (Pohang M5.5) EGS project in 2017; both of which were suspended and created public distrust as a result of seismic activity.

10. Research Gaps

Despite the growing body of literature on geothermal energy, several significant knowledge gaps remain inadequately addressed in research published. The following key gaps were identified and suggest the need for new research:

1. Low-enthalpy binary ORC resources have received less attention. Much of the available research has focused on the use of ORC technology in high-enthalpy geothermal resources found in active volcanic zones. However, there are many low- to medium-temperature ORC binary geothermal resources that still have not been studied in detail, especially throughout South Asia, Africa, and Latin America (IRENA 2017)

2. LCA data on greenhouse gas emissions from ORC plants is limited. There are very few lifecycle GHG emissions assessments of ORC binary systems available; most GHG emissions assessments of ORC binary systems are restricted to North America (i.e., U.S.A., Mexico) (Tomasini et al. 2017)

3. Long-term studies assessing sustainability of geothermal reservoirs have not been published in sufficient quantity. This lack of research regarding long-term thermal depletion and the effectiveness of re-injection of geothermal fluids creates uncertainty for planners and operators of geothermal systems located in developing countries (GEA 2019)

4. There is little to no micro-level information regarding the socio-economic impacts of geothermal development. There are very few micro- or project-specific studies detailing the impact of geothermal development on local land rights, access to surface and subsurface water resources, and the overall livelihoods of people living in the immediate vicinity of geothermal facilities (World Bank 2013)

5. The research output of geothermal-related studies has been dominated by researchers in the U.S.A. (Iceland has a significant output as well), followed by New Zealand, resulting in high-potential countries (including East Africa and Southeast Asia) receiving limited attention in terms of geothermal research output (REN21 2019).

11. Conclusion

In the context of global energy transition, geothermal energy provides a clean, abundant and renewable resource that has great potential to support this transition. Geothermal energy will be a key contributor to achieving long-term decarbonization pathways by providing continuous baseload power and having a low carbon footprint.

Two complementary conversion technologies underpin its deployment. Conventional flash steam systems dominate high-temperature resource zones, while Organic Rankine Cycle (ORC) binary closed-loop systems offer near-zero operational emissions, negligible freshwater use, and broader geographic applicability. Together, these technologies enable both high-enthalpy electricity generation and low-temperature resource utilization.

Geothermal energy development provides many social and economic co-benefits such as job creation, rural electrification, support for agricultural activity, and reduced dependence on imported fuels — all of which align with global sustainablility goals as defined under the Paris Agreement and the Sustainable Development Goals framework.

Although the global geothermal industry has the potential for large-scale expansion, factors such as high upfront costs associated with exploration, geological uncertainty, long development times, and complex regulatory processes represent major barriers to the achievement of this potential.

References

1. Bertani, R. (2016). Geothermal power generation in the world: 2010–2014 update. Geothermics, 60, 31–43.
2. DiPippo, R. (2012). Geothermal Power Plants: Principles, Applications, Case Studies (3rd ed.). Elsevier.
3. Fridleifsson, I. B., et al. (2008). The possible role of geothermal energy in climate change mitigation. IPCC Scoping Meeting, Lubeck.
4. GEA/NREL. (2020). 2019 U.S. Geothermal Power Production and District Heating Market Report. National Renewable energy laboratory. https://gdr.openei.org/submissions/1274
5. IEA. (2018). World energy outlook 2018. https://www.iea.org/reports/world-energy-outlook-2018
6. IPCC. (2014). Climate change 2014: Mitigation. WGIII, Fifth Assessment Report. Cambridge University Press.
7. IPCC. (2018). Special report on global warming of 1.5°C. https://www.ipcc.ch/sr15/
8. IRENA. (2017). Geothermal power: Technology brief. https://www.irena.org
9. IRENA. (2018). Renewable power generation costs in 2017. https://www.irena.org
10. IRENA. (2018). Renewable energy and jobs — Annual review 2018. https://www.irena.org
11. IRENA. (2019). Renewable capacity statistics 2019. https://www.irena.org
12. Lund, J. W., & Boyd, T. L. (2016). Direct utilization of geothermal energy 2015 worldwide review. Geothermics, 60, 66–93.
13. Macknick, J., et al. (2012). Operational water consumption by electricity generating technologies. Environmental Research Letters, 7(4), 045802.
14. REN21. (2019). Renewables 2019 global status report. https://www.ren21.net
15. Tomasini-Montenegro, C., et al. (2017). Life cycle assessment of geothermal power in Mexico. Energy, 138, 1128–1138.
16. Walraven, D., Laenen, B., & D'haeseleer, W. (2013). Comparison of thermodynamic cycles for power production from low-temperature geothermal heat. Energy Conversion & Management, 66, 220–233.
17. World Bank. (2013). Geothermal handbook: Planning and financing power generation. ESMAP.
18. World Bank. (2019). Kenya electricity access report. https://www.worldbank.org