WP3 - Low-Enthalpy Power Generation Technologies

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1. Executive summary

This report focuses on the application of Binary - Organic Rankine Cycle as a means of converting low-enthalpy geothermal heat (74°-177°C) into electricity. There is a massive potential for growth in the technology involved with binary cycle power generation as 68% of the global geothermal potential is less than 130°C. Due to its versatility, there has been lots of renewed interest in the research and development of its operating systems.

Current research has two areas of focus, 1, optimising the thermodynamics, and 2, optimising the techno-economics of binary plant cycles. Based on this research frontier the future of innovation will be in engineering companies that are able to both increase the efficiency of the working parts within the binary cycle system (e.g. heat exchangers, working fluid, and turbines), and with the ability to scale or modulate the plant designs to optimally fit the available geothermal resource (or other waste heat resources), meet the needs of its energy consumers, and reduce overall cost of electricity.

This report has also outlined the current market status of active or developing binary cycle technology providers. These developers represent some of the most promising potential partners in growing low-enthalpy geothermal electricity generation. A summary of each of these providers and figures including kW capacity, temperature and flow inputs, efficiency, and life cycle assessment, have been provided for each technology when available.

2. Introduction

Traditionally, geothermal energy over the temperature of 180°C can be used to generate electricity. High-enthalpy geothermal resources are able to produce this temperature at relatively shallow depths. This electricity generation can produce 24hrs a day, providing a valuable baseline for other intermittent renewable electricity producers (solar and wind). However, these can only be found in a few unique geological locations in the world, (e.g. New Zealand, Iceland, Kenya, Italy, etc.). The conversion efficiency of heat to power in these traditional energy plants ranges from 1% to 21%, with a global average of 12% [1].

The majority of geothermal resources globally are low-enthalpy, producing lower temperatures which cannot be directly used for electricity generation. However, there is an emerging industry for modular technology to be able to provide electricity from low enthalpy resources. By implementing this technology, you could create renewable electricity from low-enthalpy resources worldwide.

This report will explain the technology and how it is able to convert low temperature resources to electricity. It will also outline the low enthalpy power-modules currently available on the market with parameters included.

3. Technology Overview

It is generally agreed by researchers that there are five standard power configurations developed for geothermal plants: 1. dry steam, 2. single flash, 3. double flash, 4. binary (Organic Rankine Kalina Cycle), and 5. advanced geothermal

[1] Zarrouk, S.J. and Moon, H., 2014. Efficiency of geothermal power plants: A worldwide review. Geothermics, 51, pp.142-153.

energy conversion systems (hybrid single-double-flash systems - triple flash, hybrid flash-binary systems, hybrid fossil-geothermal systems, hybrid other-renewable heat source-geothermal systems, and hybrid back pressure system)[2]. These geothermal power plants can be further classified into the two groups, steam cycles for wells with higher enthalpies (>177°C) and binary cycles for wells with lower enthalpies (74°-177°C).

While steam cycles will likely remain the competitive technology for large-scale heat recovery and geothermal power generation, a world geothermal resource assessment found that approximately 68% of the total geothermal resources are temperatures lower than 130 °C (mostly for direct heat applications) and the remaining resources are temperatures higher than 130 °C (suitable for electricity generation). Thus, Binary – Organic Rankine Cycle power plants will play a vital role to help the world use its abundant low temperature geothermal resource[3].

Binary cycle power plants operate on geothermal fluids from 74°-177°C. These systems use an Organic Rankine Cycle (ORC) where geothermal fluids are passed through a heat exchanger where it heats a working fluid (fig. 1). This working fluid is usually made of an organic compound with a low boiling point (e.g., isobutene, isopentane, propane, freon, or ammonia) but can also use supercritical fluids (e.g., CO_2). The expanding force of the vaporised working fluid turns a turbine to generate power[4]. If the power plant uses air cooling, then both the geothermal fluid and working fluid are recycled in a self-contained, closed loop effectively making it an emission free system. Binary power plants were responsible for 14% of the world's installed geothermal electricity capacity in 2014[5] and are often constructed as linked modular units of a few MW_e in capacity.

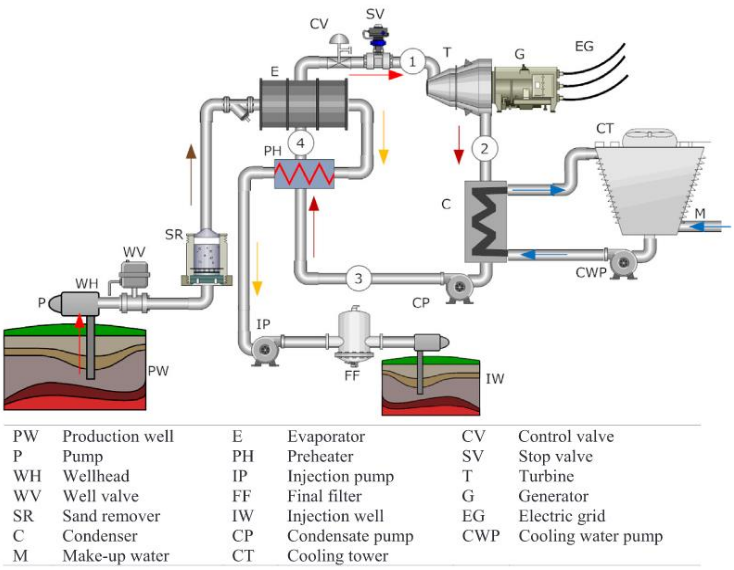

Figure 1 Basic binary cycle geothermal power plant[6]

Other potential applications of the binary plant can be seen outside of geothermal systems. The ORC also provides an

[2] Moya, D., Aldás, C., & Kaparaju, P. (2018). Geothermal energy: Power plant technology and direct heat applications. *Renewable and Sustainable Energy Reviews*, *94*, 889–901. https://doi.org/10.1016/j.rser.2018.06.047
[3] Stefansson V. World geothermal assessment. In: Proceedings of the Conference World geothermal assessment. p. 24–9.
[4] Hernández Ochoa, A. F., Aragón Aguilar, A., & Franco Nava, J. M. (2021). An up-to-date perspective of geothermal power technology. In *Sustainable Fuel Technologies Handbook* (pp. 201–238). Elsevier. https://doi.org/10.1016/B978-0-12-822989-7.00008-1
[5] Lund, J. W., & Boyd, T. L. (2016). Direct utilization of geothermal energy 2015 worldwide review. *Geothermics*, *60*, 66–93. https://doi.org/10.1016/j.geothermics.2015.11.004
[6] Moya, D., Aldás, C., & Kaparaju, P. (2018). Geothermal energy: Power plant technology and direct heat applications. *Renewable and Sustainable Energy Reviews*, *94*, 889–901. https://doi.org/10.1016/j.rser.2018.06.047

opportunity to exploit heat produced from biomass, solar and exhaust gases from engines and other industrial processes[7] (examples discussed in appx.).

4. Plant Optimisation and Future Innovation

There are two areas of focus in regard to optimising binary-ORC plants and the future of innovation. The first is optimising the thermodynamics (i.e. working fluid and cycle parameters) and the second is the techno-economic optimization of each plant.

A number of scientific studies have been focused on the thermodynamic optimisation of binary-ORC based on the selection of working fluids and the corresponding cycle parameters for its various applications (waste heat recovery, biomass combustion, solar heat, geothermal, geothermal-solar hybrids, advanced cycle, and other mixtures). Results show configurations based on supercritical cycles, employing fluids with a critical temperature slightly lower than the temperature of the geothermal source, lead to the highest efficiencies for most of the investigated cases. Also, out of 54 working fluids in 6 different cycle configurations, for low geothermal brine temperature (120 °C), the optimal fluid is decafluorobutane C_4F_{10}, and for higher temperature (180 °C), the optimal fluid is R236ea[8].

Techno-economic analysis also shows it is necessary to perform optimization on the basis of specific plant cost. It was confirmed that the configurations based on supercritical cycles, employing fluids with a critical temperature slightly lower than the temperature of the geothermal source, lead to the lowest electricity cost and therefore most techno-economically efficient plant[9] .

The future of innovation in optimising binary-ORC plants likely lies in engineering new working fluids, primary heat exchangers, and turbines that maximise plant efficiency or improve its power output while keeping in mind the development costs and geothermal resource. Most importantly its operators must take into consideration individual plant needs (desired power output) and their geothermal capability (i.e., production temperatures, reinjection temperatures, and subsurface well design). In this sense

[7] Goldstein, B., G. Hiriart, R. Bertani, C. Bromley, L. Gutiérrez-Negrín, E. Huenges, H. Muraoka, A. Ragnarsson, J. Tester, V. Zui, (2011): Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/geothermal-energy/

[8] Astolfi, M., Romano, M. C., Bombarda, P., & Macchi, E. (2014). Binary ORC (organic Rankine cycles) power plants for the exploitation of medium–low temperature geothermal sources – Part A: Thermodynamic optimization. *Energy*, *66*, 423–434. https://doi.org/10.1016/j.energy.2013.11.056

[9] Astolfi, M., Romano, M. C., Bombarda, P., & Macchi, E. (2014). Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium–low temperature geothermal sources – Part B: Techno-economic optimization. *Energy*, *66*, 435–446. https://doi.org/10.1016/j.energy.2013.11.057

the most successful innovations will be with the companies that are able to quickly modulate their technology to maximise the output of each plant with its customers in mind.

5. Current Market for Technology

There is an emerging market for modular technologies which convert low enthalpy geothermal energy, and waste heat energy, to electricity. All companies in this chapter are active, and currently operational.

Climeon is a world leader in converting low temperature heat into clean electricity. They use a patented, Heat Power system that focuses on decentralised binary heat power generation. Their system uses the principles of an ORC but at lower pressure levels, exploiting the temperature difference between hot and cold water to generate electricity.

The technology uses ORC technology, using a hot, high-pressured source, and a cold, low pressured source to generate flow, turning a turbine and generating electricity. Each module consists of an evaporator which transfers heat to the working fluid, a turbine generator for conversion of thermal energy to electricity, and a cooling system that transfers heat out of the module to the cooling water circuit.

The modules are 8 tonnes in weight, 8m^3 in volume and can produce 150 kW. The heat source required is between 70 – 120°C and a flow rate of 10 – 40 L/s. The cold source must lie in the range of 0 – 30°C and a flow rate of 10 – 40 L/s.

Climeon claims to have the world's most efficient low heat to electricity technology, with 50% more than its competitors.

ClimeOn Case Study

In 2018 Climeon installed four heat power modules onto one of Varmaorka geothermal power plants in Flúðir, Iceland, giving the power plant a maximum capacity of 600 kW. Varmaorka specialises in heat temperatures of ~100°C.

A further four heat power modules are being commissioned in 2021, doubling production capacity to 1.2 MW.

Enogia specialises in the design of micro-turbomachinery in their heat-to-electricity conversion in ORC systems. Enogia has a range of modular devices, from 10kW to 180 kW in electricity output. These modules focus on low temperature geothermal, and oil and gas wells. Enogia worked on a number of multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems exploration and Exploitation Techniques (MEET) projects , providing small ORC units to a number of research sites across Europe. MEET is an EU funded project looking at various ways to increase geothermal usage[10]. This includes enhancing heat-to-power conversion at low temperature (60-90°C) by using smart mobile Organic Rankine Cycle units. Enogia was also included in FT 1000 - Europe's Fastest Growing Companies 2021, (998/1000)[11]

[10] https://www.meet-h2020.com/

[11] https://www.ft.com/content/8b37a92b-15e6-4b9c-8427-315a8b5f4332

		Design Point	Test
Brine			
Temperature Inlet	°C	115	99
Temperature Outlet	°C	93.3	86.9
Flow	m^3/h	25.2	27
Thermal Power	kWth	640.52	526.65
Cold Loop			
Temperature Inlet	°C	10	31.37
Temperature Outlet	°C	38	39.6
Flow	m^3/h	19.69	20
Thermal Power	kWth	640.52	487.16
Working Fluid (R1233ZD)			
Temperature Evaporator Outlet (T3)	°C	98.73	96
Pressure Evaporator Outlet (P3)	bar	9.49	7.36
Temperature Condenser Outlet (T1)	°C	37.83	33.4
Pressure condenser Outlet (P4)	bar	2.22	2.18
Turbine			
Turbine Output power	kW	40.23	27.75
Efficiency	%	6.28	5.3
Pressure ratio		4.27	3.38

Figure 2. Performance of Enogia ORC unit at Kruma, with the design specifications compared to the actual test outcomes.

Enogia Case Study

Krauma Geothermal baths and spa in Borgarfjördur, Iceland, produces 40kW from Enogia's small power modules[12]. They have a temperature of 100°C with a flow rate of 180 L/s. The site is a demonstration site for MEET. The results of the research project were positive, with 82% of the theoretical heat, the machine produced 70% of the expected electrical power The cost of the project was estimated to be between EUR 180,000 – 220,000.

Munich based Orcan Energy[13] was established in 2008 and provides energy-efficient solutions for the conversion of waste heat to using the ORC. Though the company is currently concentrating on waste heat, the temperature requirements as low as 60°C means it could be potentially implemented on low-enthalpy geothermal systems. Orcan Energy has over 200 operational units world wide, saving 20,000 t of carbon.

Orcan Case Study

In April 2021, Orcan Energy partnered with E.ON to build six ORC container modules onto a geothermal site located in Kirchweidach, Upper Bavaria, Germany. The output of the modules is 1 MW, saving an estimated 4,000 tons of CO_2 annually[14]. The Orcan Energy ORC module was chosen because it adapts to both seasonal conditions and sporadic heat consumers.

Established in 2005 in Reno, Nevada, ElectraTherm provides low -temperature and waste heat recovery solutions to improve energy efficiency and produce power. The system uses the ORC with other proprietary technologies (not disclosed). Their Power+ generator has a maximum electrical output of up to 150 kW. The 6500B module is 2 m x 3.3 m x 2.5 m (WxLxH). The 4400B/4400B+ modules can generate up to 75 KW, whilst the 6500B/6500B+ units can generate up to 150 KW. ElectraTherm has 100 ORC units in over 14 countries.

ElectraTherm acquired BITZER in 2016, the world's largest independent manufacturer of industrial and commercial refrigeration equipment. In 2019 ElectraTherm integrated the twin screw expander, allowing for dual-phase flow for disruptions in both temperature and flow. This resulted in a 15% performance improvement and lowered costs.

ElectraTherm Case Study

In 2016, ElectraTherm commissioned a single Power+ Generator 4400 in Beppu, Japan. This was for a local community's

[12] https://www.meet-h2020.com/demonstration-sites/krauma/
[13] https://www.orcan-energy.com/en/
[14] https://www.thinkgeoenergy.com/orcan-energy-implements-first-geothermal-project-in-germany/

heating system for domestic heating needs. At this site, the geothermal steam provides varying flows at approximately 110°C with a flow rate of 12 L/s. The system produces an output of 60 kWe.

FeTu are a novel bare shaft compressor technology[15]. It focusses on low-grade waste heat recovery but could also be applied to low-grade geothermal. The product is still in an early development phase (readiness level 4-5, see appx. 7.3.) with testing completed in 2019 in collaboration with the University of Bath[16]. They recently exhibited at the 2022 All-Energy Conference in Glasgow and are currently looking for investment to drive their next stage of development.

A non-phase change fluid (CO_2) is worked between a volumetric offset in each half of the FeTu device. The system benefits from work on both high and low pressure sides. A high and a low pressure domain are each excited via heat exchangers, fluid expands and contracts whilst travelling around a closed circuit. The FeTu rotor forms a boundary between the two pressure domains and is driven by the combined forces of both the high and low pressure zones.

Summary Figures for Current Market Technology

Technology Provider	kW Capacity	Heat Source		Cold Source		Efficiency	Technology readiness level (TRL) (see appx.)	Lifetime (years)
		Temperature input	Flow input	Temperature input	Flow input			
Climeon (HP 150 UNIT)	150 kWe	80 °C and 120 °C	10 – 35 L/s	0 - 30°C	10 – 35 L/s	n/a	9	30
Enogia ENO-10LT	10 – 180 kWe	70-120°C	7 – 180 L/s	0 - 60°C	n/a	n/a	7-9	20
Orcan Energy EP 150.200	50 kWe – several MWe	80-150°C	n/a	n/a	n/a	n/a	9	15
ElectraTherm 4400B	75 kWe	70 - 116°C	3 - 15 L/s	4 - 65°C	6 - 18 L/s	10%	9	20
ElectraTherm 4400B+	75 kWe	70 - 150°C	3 - 15 L/s	4 - 65°C	6 - 18 L/s	10%	9	20
ElectraTherm 6500B	125kWe	70 - 132°C	3 - 25 L/s	4 - 65°C	9 - 26 L/s	10%	9	20
ElectraTherm 6500B+	150 kWe	70 - 150°C	3 - 25 L/s	4 - 65°C	9 - 26 L/s	10%	9	20
FeTu Roticulate	unknown	70°C min	pending research	pending research	pending research	pending research	4	pending research

15 https://www.fetu.co.uk/closed-loop-heat-recovery

16 Zhang, Y., Madamedon, M., Copeland, C., Fenton, J.P., Subert, J., Hinchliffe, K., Arbon, I.M. and Leefe, S., 2019, August. The reticulating concept air compressor: experimental and numerical investigation. In *IOP Conference Series: Materials Science and Engineering* (Vol. 604, No. 1, p. 012070). IOP Publishing.

Table 6 Summary table of all low-enthalpy to power technologies

Provider Contact Details

Providor	Website	Location	Contact Details	CEO
Climeon	https://climeon.com/	Sweden	n/a	Lena Sundquist
Enogia	https://enogia.com/	France	info@enogia.com	Arthur Leroux
Orcan Energy	https://www.orcan-energy.com	Germany	info@orcan-energy.com	Andreas Sichert
Electratherm	https://electratherm.com/	US	sales@electratherm.com	n/a
Fetu	https://www.fetu.co.uk/	UK	info@fetu.co.uk	Jonathan Fenton CEO

Table 7 Contact details of all low-enthalpy to power technologies

6. Conclusion

[Conclusion to be finalised at clients request]

7. Appendix

Aluminium Melting for thermal storage

There are other companies looking at low enthalpy electricity conversion, from a different source than geothermal. For example, Azelio[17] is not based on receiving geothermal energy, instead uses solar energy. The solar energy is concentrated onto a receiver and absorbs the heat, using the heat energy to melt an aluminium alloy that makes up part of the thermal storage solution. It has an efficiency of 90% (solar energy to electricity). A heat transfer fluid is driving around the storage unit melting a recycled aluminium alloy at 60DegC, the phase changes from solid to liquid and the storage unit can harness the heat for a longer period. Heat is then extracted from the store, on demand, into a stirling engine producing zero emission at full power for 14 hours. It also generates heat at 55-65DegC.The TES.POD 1.0 Modular has an electrical output from 0.1 to 100MW. They are currently building a demonstrator project in Åmål, Sweden.

Echogen Power System - sCO_2 Working Fluid

The Echogen Power System's[18] heat engine uses supercritical carbon dioxide (sCO_2) as the working fluid, in a closed-loop cycle. sCO_2 has the benefit compared to steam and organic Rankine cycle alternatives, to start and operate autonomously. sCO_2 can interact more directly with the heat source than water/steam, eliminating the need for a secondary thermal loop, typically required in traditional waste heat recovery systems. It has no water consumption and no risk of freezing. They have commissioned the first sCO_2 power plant pilot project in 2021. Initially they are concentrating on high temperature waste heat, however as the technology develops it could be used for lower temperature sources.

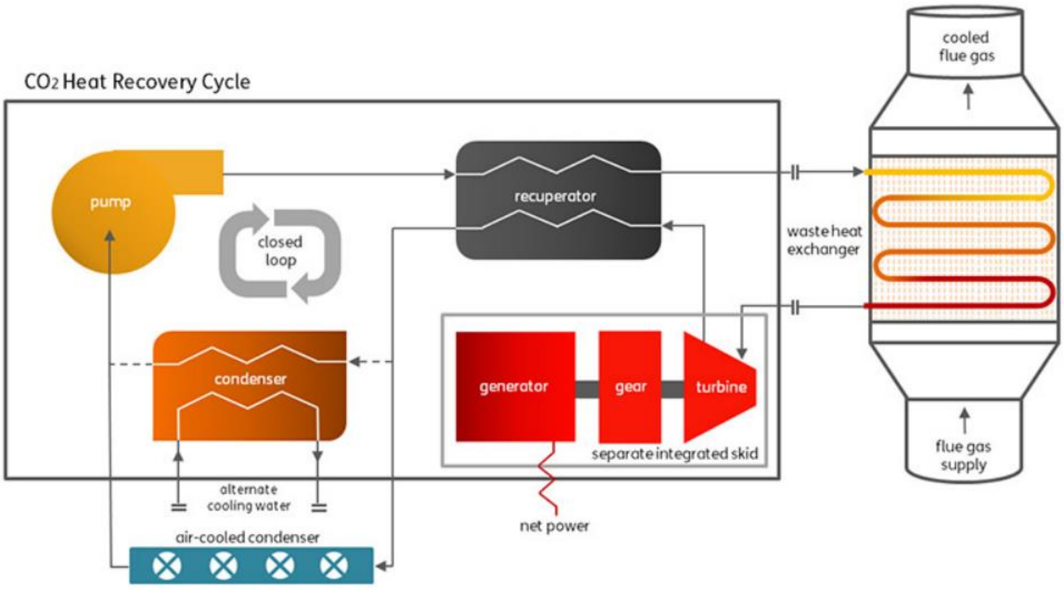

Figure 3 EPS sCO2 system schematic

[17] https://www.azelio.com
[18] https://www.echogen.com

Echogen Case Study

Echogen Power Systems is partnered with Siemens Energy to build a waste to heat pilot project in Alberta, Canada. It is expected to be commissioned towards the end of 2022, producing enough electricity to power more than 10,000 homes, and greenhouse gas reduction of 44,000t sCO_2[19]. The power plant is funded in part by Emissions Reduction Alberta, who contributed $8 million in funding.

Technology Readiness Level[20]

[19] https://www.echogen.com/news-resources/news-events/siemens-energy-to-build-first-of-its-kind-waste-heat-to-power-facility-in-canada

[20] www.twi-global.com

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