Integration of ORC geothermal power plant with different modern technologies for energy recovery using base data from Upper Rhine Graben, Germany

Long Version

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Abstract
Geothermal energy is gradually turning into one of the major sources of renewable energy in the world. The relevance of Organic Rankine Cycle is also escalating together with geothermal energy in Germany due to its efficient conversion capabilities of medium enthalpy hydrothermal sources. In this thesis, four energy recovery options from a geothermal ORC power plant are evaluated: Thermoelectric Generator (TEG) and Thermomagnetic Generator (TMG) which use waste heat as energy source and Pressure Retarded Osmosis (PRO) and Reverse Electrodialysis (RED) which uses salinity gradient as energy source.
Based on the data collected from Upper Rhein Graben and ongoing projects implemented by Rud. Otto Meyer Technik GmbH & Co. KG as well as Turboden S.p.A. the efficiencies, power outputs and total investment cost of the ORC geothermal power plant are determined. Only TEG and PRO were found competitive and suitable among the four technologies in which PRO was found to have better current suitability and performance based on the specified boundary conditions.

1. Introduction

Efficient, renewable and environmental friendly energy creation has become an inevitable need for a sustainable future and to achieve this, the maximum utilisation of every energy source is necessary. A major part of all energy generation processes is lost as waste heat. The conversion of this primary form of energy, heat energy, is a prominent solution for many of our energy crises. Together with Waste Heat Recovery (WHR), the exploitation possibilities of Saline Gradient Energy (SGE) from an ORC geothermal power plant using base data from Upper Rhein Graben (URG) is evaluated in this thesis. URG is a major geothermal reserve in central Europe which is characterized by higher thermal gradients, salinity levels and mineral concentrations. Since URG is a hydrothermal reservoir having natural permeabilities, the execution of an ORC binary power plant is studied. Also, the coupling of four energy recovery options before the reinjection of brine is also analysed.

Thermoelectric Generators (TEG) are generators that convert heat energy directly to electric energy using solid state materials. The electricity is generated when a temperature gradient is induced between two semiconductors (n- and p-type) placed between a heat source and heat sink. This heat flow induces the electrons and holes to flow from the hotter side to the cooler side.

Thermomagnetic Generator or TMG is a competing technology with TEG which functions based on the thermomagnetic properties of the ferromagnetic materials used, mainly on Curie temperature or transition temperature. Ferromagnetic materials lose their magnetic property at a certain temperature called Curie temperature and this change in magnetism can be utilized for converting heat energy to electrical energy.

Pressure Retarded Osmosis (PRO) and Reverse Electrodialysis (RED) are the two typical methods for extracting osmotic energy. The major difference between PRO and RED lies in its membrane systems. RED is more like a battery or cell system which is the reverse process of electrodialysis. It converts osmotic energy or chemical energy directly to electrical energy using Ion Exchange Membranes. PRO is based on osmosis principle, where semipermeable membranes are used for transferring water molecules from fresh water to higher saline sources (geothermal brine). The excess volume of diluted brine is converted into electricity using generators.

2. Performance of ORC geothermal Power Plant

Based on the two brine input temperatures of 175 °C and 185 °C and constant brine output temperature of 65 °C, different efficiencies of ORC are calculated using the data and equations shown in table 3.1 and 3.2 respectively. The calculations were done using base data received from Rud. Otto Meyer Technik GmbH & Co. KG as well as Turboden S.p.A. The ORC cycle efficiency, thermal efficiency, Carnot efficiency and relative efficiency (cycle efficiency with respect to Carnot efficiency) are depicted in the diagram given below shown below. The first cycle with brine input temperature 175 °C (ΔT =110 °C) produced a net electrical output of **5.63 MW** at an efficiency of **15.92%** and the second with 185 °C (ΔT =120 °C) produced a net electrical output of **7.49 MW** at an efficiency of **20.05%**. This extra 10 °C has also induced around 10% increase in relative efficiency from 68.72 to 78.42%. However, this efficiency increase also depends on other factors which was not in the scope of the thesis and is calculated using the collected base data.

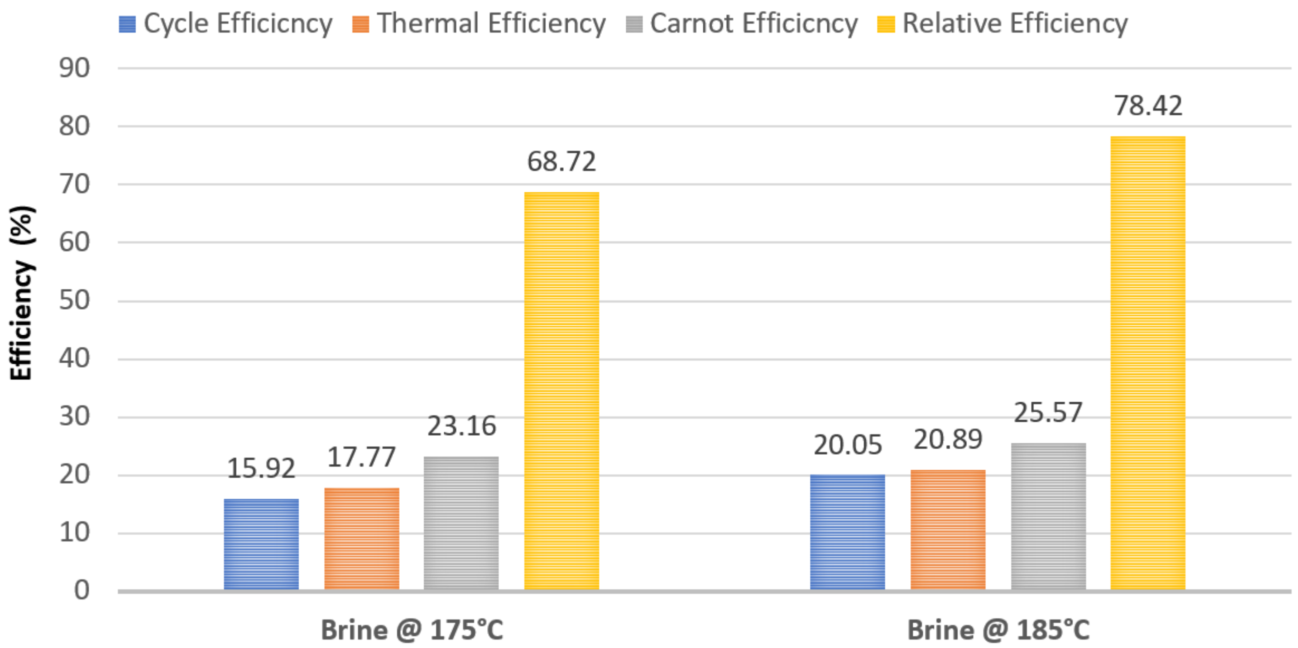

Figure 1. Different efficiencies of an ORC geothermal power plant at two brine input temperatures

3. Technology Analysis

TEG and TMG are two prominent waste heat energy recovery methods, but their operating conditions are different. The figure below shows the comparison of the relative efficiencies of the recent best

TEG ($Bi_2Te_{2.79}Se_{.021}$ and PEDOT:PSS) and TMG (La-Fe-CO-Si) materials. From the diagram it is clear that, TMG is more efficient when the temperature difference between heat sink and heat source is less than 10 °C. In our case ∆T = 50 °C and TEG is found more suitable for coupling with ORC geothermal power plant.

Both PRO and RED have the potential to convert the SGE, but PRO has better power densities and efficiency when compared to RED. PRO has higher efficiencies in between 54–56% and power densities in between 2.4–38 W/m2 while RED only showed 18–38% and 0.77–1.2 W/m2 respectively (Yip and Elimelech 2014, Zhang et al., 2019). The suitability of RED is higher in regions where salinity is less since it is less dependent on the increasing salt concentration, e.g., sea and river water as source energy. The PRO is the better option when it comes to higher salinity concentrations, and is the preferred method for brines (Budde, 2021).

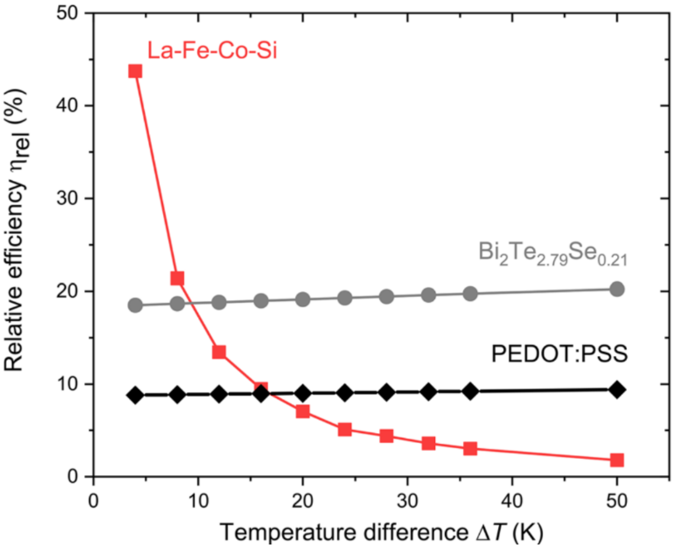

Figure 2. Comparison of relative efficiencies of TMG and TEG Source: Dzekan et al. (2021)

3.1. TEG coupled on the brine side

The proposed coupling of TEG array before the reinjection of brine is depicted in the flow diagram given below. From the currently available thermoelectric modules in lower temperatures ranges four suitable modules are selected, among them Thermonamic Electronics Corporation limited, China (Product details: Thermonamic.com (2023) provides a TEG system suitable for geothermal heating purpose commercially which also includes heat sink and heat source. A total number of around 1500 units of such TEG systems will be required. The expected gross power of the TEG-WHR system with ∆T of 50 °C is 28.5 kW. However, the required pump power for circulating 85 kg/s of thermal water and cool water is 10KW each. This reduces the total net power of the system drastically to 8.5 kW which is not profitable (Table 1). The total costs could be reduced considerably by substituting large TEG system.

Table 1. Cost Analysis

Parameter	Amount	Unit
Total investment cost	1,823,242	€
Unit power	19	W
Number of TEGs	1500	pcs
Gross power	28.5	kW
Pump power	20	kW
Net power	8.5	kW
Commercial selling cost per KW for electricity in Germany	0,18	€/kWH
Full load hours in a year	8400	H
Income per year	12,852	€
Payback period	142	years

A projection of performance and profitability of TEG system at higher temperature differences are also done which is shown in the figures below.

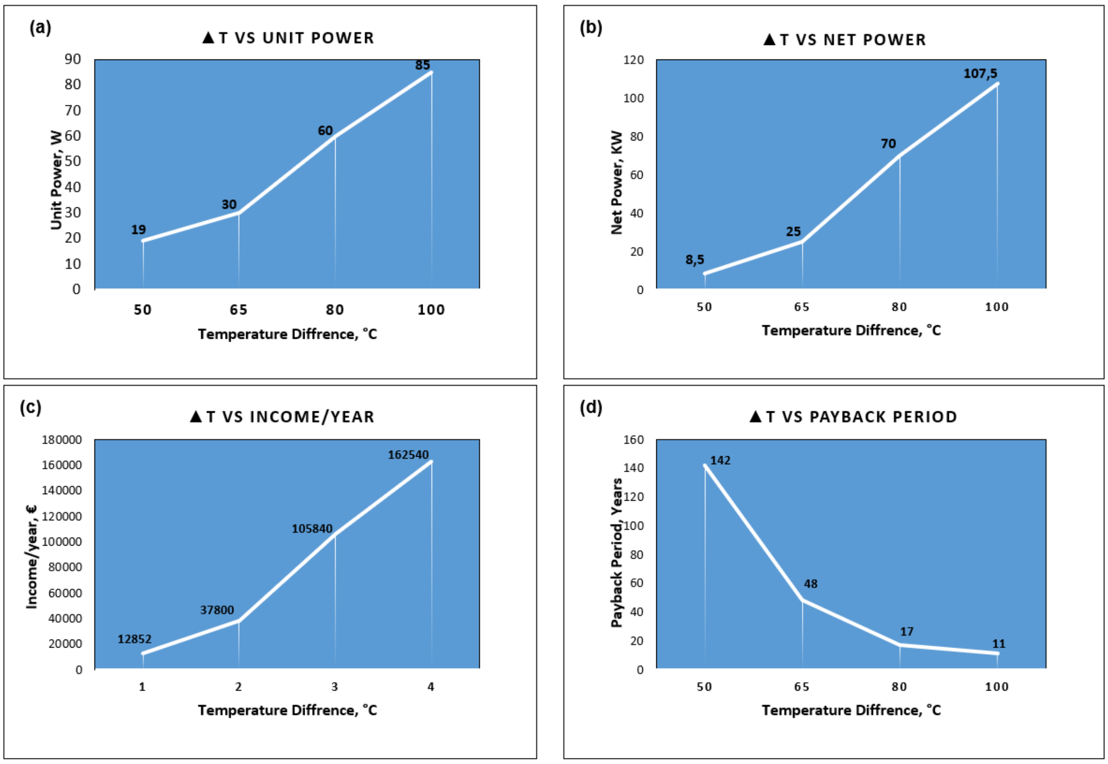

Figure 3. Performance and profitability projection

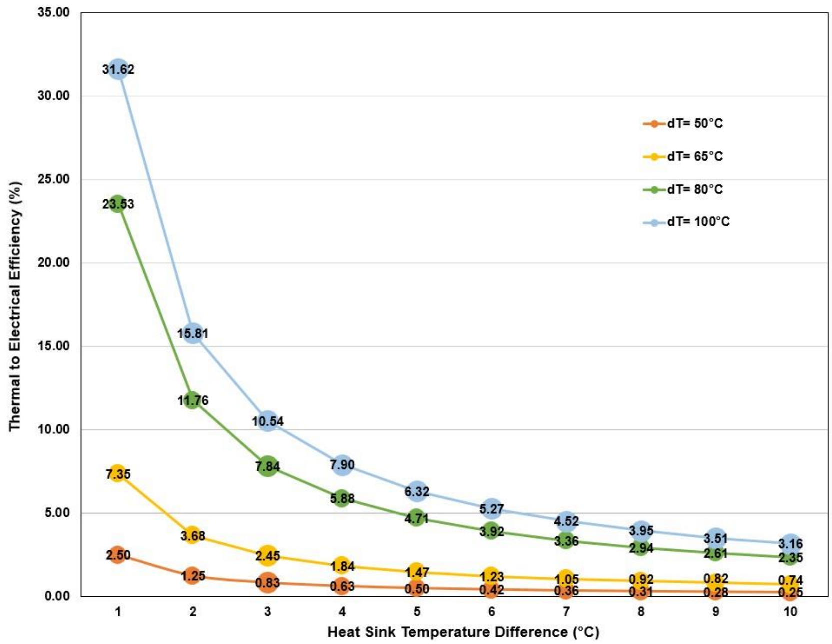

Figure 4. Efficiency projection

In addition to the proposed system, I also did some inquiries to TEGma, a company that produces larger TEG-WHR systems (TEGma.no, 2023). These systems can produce a net electrical output from 20 kW to 200 kW which can also be combined. They can use water, steam and oil as heat of source with a wide extend of operating temperatures from 10 °C to 220 °C at the heat source side and from 50 °C to -50 °C at the heat sink side. However, from the responses received, a minimum temperature difference of 90 °C is required for the commercial utilisation of their TEG systems. Anyhow, the increase of temperature difference from 50 °C to 90 °C cannot be considered or executed. In the temperature difference of 90 °C, different other technologies must also be considered and analysed.

3.2. PRO coupled on the brine side

The utilisation of SGE on the brine side and its calculations are found to be highly complex and require a lot more data both theoretical and experimental. Currently, SaltPower (SaltPower.net, 2023) is the only company that I have found which commercially produces energy from SGE who are also in a progressing stage. Because of these reasons, the estimation of profitability and efficiency of a PRO power plant was not included in the scope of this thesis. From the detailed final report of projects conducted by SaltPower named "Osmotic power generation from geothermal wells" (Energiforskning.dk, 2023) some ideas and suggestions are achieved.

Some inquiries were put forward to SaltPower for understanding the feasibility of coupling geothermal power plant with PRO process. Based on this, brine having TDS values around 120 g/l and a brine flow rate of 85 kg/s is expected to have a net power output of 50 kW. However, this will be uneconomical and for a profitable energy recovery system a minimum TDS value of at least 200 g/l or a salinity of 20 wt% is required. With the increase of TDS value, the power output will also be increased proportionally. For another case with the same flow rate of 85 kg/s and a TDS value of 300 g/l or above, an electrical output of 300 kW can be expected.

Even with higher salinities, a major challenge remains for the PRO technology. An increased volume of almost two times of the geothermal brine should be disposed in proper ways without any environmental impacts and by maintaining the profitability. This should be considered as the most significant factor in deciding the overall suitability of the project. Only the same amount of brine can be re-injected back to deep reservoir and the remaining geothermal brine should be treated or disposed in proper ways without causing any environmental impacts and financial risks. In addition, the geothermal brine should also be cooled down to a temperature of 30 °C for the best performance of the osmotic power plant.

4. Conclusion

The exploitation of SGE using PRO is possible if the minimum TDS value of 200 g/l is available and the challenge of increased diluted geothermal brine is resolved. The current utilisation of TEG for lower temperature differences is not feasible (a minimum ΔT of 90°C is required). However, by substituting larger TEG units, both the cost and space requirements could be reduced. The application of these energy recovery technologies should never hinder the ORC process. Currently, PRO shows better suitability for energy recovery from an ORC geothermal power plant.

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