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Optimizing the Potential of Geothermal Resources in Steam Power Plants with Retrofitted Binary Technology: Exergy's Case Study in the Philippines, Mindanao 3 Power Plant

Marco Frassinetti, Riccardo Pezzoni, Giacomo Rufo Menghetti

Exergy International srl. Via Santa Rita 14, 21057 Olgiate Olona (VA), Italy

m.frassinetti@exergy.it, r.pezzoni@exergy.it, g.menghetti@exergy.it

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ABSTRACT

In the Asia Pacific Region and in many other countries at the edge of the so-called ring of fire, the geothermal power potential is huge. The main technology used to harness these resources has traditionally been flash steam turbine power plant and there is a wide fleet in operation in this geographical area.

Although efficient and reliable these systems waste a significant part of the thermal capacity available in the liquid phase (brine). This heat energy could be efficiently exploited to maximize the geothermal potential of a resource in a steam field and increase the efficiency and power capacity of the plant without the need of risky investments in new exploration and drilling.

It is possible to profitably recover the heat energy contained into the geothermal brine to produce additional electricity at site by retrofitting a binary cycle to an existing steam power plant.

The following paper describe in detail a recent application of Exergy's advanced binary system utilizing the Radial Outflow Turbine technology for brine recovery in the Mindanao 3 flash power plant in the Philippines. The paper will show the advantages of this solution that can help increase the rated electrical power output of a steam field by 30% thus increasing its efficiency and profitability with no additional environmental footprint.

1. INTRODUCTION

Global warming is defined as the most critical challenge of our times. For this reason, governments, investors, companies, and private citizens are initiating new forms of cooperation, initiatives and incentives to find new solutions capable to reduce the emissions. The decrease of the carbon intensity of the energy sector is one of the most relevant issue, not only in the electricity generation sector, but also in other activities like transportation, responsible for a large share of the emissions, or heating and cooling. Certainly, the exploitation of renewable energies for power generation, such as photovoltaic and wind, can contribute to a clean energy future. Nevertheless, the non-dispatchability of these sources cause grid stability problem. This issue can be solved by further development of geothermal energy and biomass usages, together with new resources (tidal energy, wave power, storage systems) and with hydroelectric. Those power generation plants can guarantee both clean energy and sustainable base load power generation system.

2. GEOTHERMAL POWER GENERATION

2.1 Geothermal State of the art

In the world, the installed capacity for power production from geothermal resources was about 16 GW in 2020, while other thermal usages accounted for more than 70 GW of thermal power. Thermal usages are either direct, such as air conditioning and district heating or cooling, or ground-source heat pumps (GSHP) (Huttrer, 2020).

There is an important difference between the thermal usage and power generation. The latter requires a series of factor, such as water in reservoir among all, and heat available close to the crust, while the first one exploits the Earth average gradient so it can be applied everywhere in the world.

The factors and conditions that influence the possibility of exploiting geothermal for power generation limit its use to only a small number of nations, all of them characterized by consistent geological activities. About 95% of the installed capacity is present in 10 countries (USA, Indonesia, Philippines, Turkey, Kenya, Mexico, New Zealand, Italy, Iceland and Japan). Obviously, this distribution is due to the source's availability and stability but also is strongly affected by specific policies that have been driving the market towards desired directions.

Over the next five years, the expected growth of the electricity generated by geothermal sources is about +20% (+3.4 GW of installed capacity). Compared to the expected PV growth, which is about +360 GW (100 times more than geothermal, +60% with respects to installed plants in 2020), it looks clear that there are some issues and obstacles linked to the development of the geothermal source that must be taken into account in order to tap a much wider potential.

2.2 Source Uncertainty, Key Threat to Geothermal Development

Developing a new geothermal resource is a long and expensive process. The initial costs are very high, as there's the need to assess the presence of the resource and the initial investments are required upfront. First moves are very risks since they could bring to disappointing results. For these reasons, the cost of capital is high, and so any potential investor is willing to proceed with all the risks only if the investment is profitable enough. Costs and risks associated to exploration of geothermal energy have been the main threat to the development of new geothermal projects worldwide and strongly affect the price of geothermal electricity (Mulazzani, 2016). From the beginning of the investments to the first revenue stream a lot of years pass. For greenfield projects, where the site preparation is another aspect that must be accounted, this amount of time reaches more than five years, which is not an uncommon value for geothermal projects. Other aspects that must be considered is the stability of the source. This factor is analyzed and investigated during operation, and especially in case of bad or no reinjection, it can reduce over time.

2.3 Flash Cycles, Main Paradigm for Geothermal Power Generation

Flash cycles are the most simple and conventional system used for power generation in geothermal high-temperature applications. Since most geothermal wells produce fluids which have two different phases, brine and steam (together with non-condensable gases and solid particles), the steam and gases must be split from the heavier components using separators. Then, while the liquid phase (brine) is reinjected, the saturated steam enters the steam turbine, which is coupled with an electrical generator in order to produce power. At the outlet of the steam turbine, there is a condenser, generally a direct contact condenser, where a cooling fluid achieves the condensation of the steam. At the end the condensate is usually reinjected together with the cooling fluid and the hot brine that arrives form the separator. In Figure 1 a simplified diagram of the flash cycle is represented.

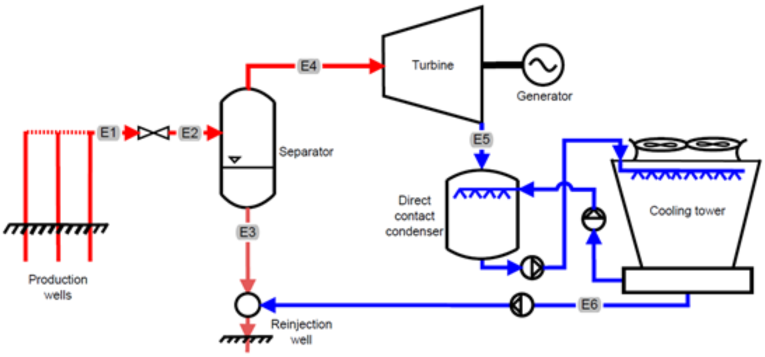

Figure 1: Single Flash Steam Power Plant

2.4 Binary Plants, ORC Sweet Spot in Geothermal Applications

Binary plants have two different fluids, that never mix, and so two different cycles: the first is where the working fluid absorbs heat via the shell-and-tube heat exchangers from the geothermal fluid, either steam or brine; the second cycle is the ORC. The second fluid is an organic fluid that is evaporated and then sent to a proper turbine coupled with its generator. At the end the fluid is condensed with air or water as cooling agent and pumped again with a feed pump. In Figure 2 an example of a binary cycle is shown.

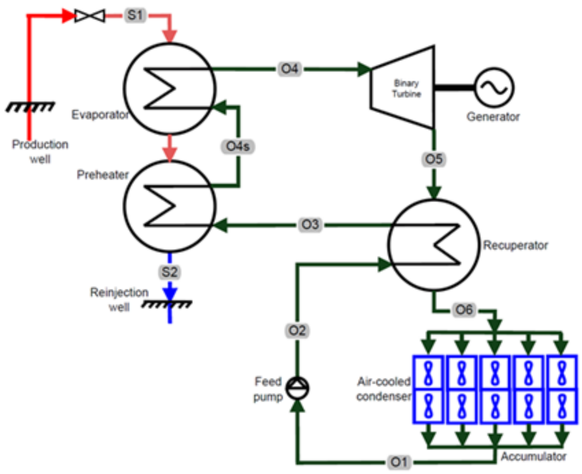

Figure 2: ORC Binary Power Plant, with one pressure level, a recuperator and an Air-Cooled Condenser

It is worth underlining that the Organic Rankine Cycle just described is a closed loop with **no interaction with the geothermal fluid**, meaning that all O&M issues related to fouling or corrosion will not affect any of the components of the ORC, but remain limited to the geothermal circuit and the tube-side of the heat exchangers. Other advantages of using an organic fluid in binary plants can be related either to efficiency increase or economic gain. First of all, all organic fluids have a shape of the saturation dome that allows a **dry expansion process**, meaning that there is no risk of having liquid formation in the turbine, which is on the other hand typical of water steam turbines. In this way, in any off-design condition there is no eventuality of erosion, caused by droplets impacting at high speed against the blades of the expander and resulting in a reduction of the useful life of the turbine. Another advantage is the possibility to **avoid any water consumption**, especially where this is a precious resource, thanks to the use of an air-cooled condenser; nevertheless, if water and namely condensate is freely available, an indirect water-cooled condenser can be used to increase the cost-effectiveness of the solution. Moreover, the possibility to pick the working fluid across a wide selection of candidates, allows an overall optimization that can maximize the cost-efficiency of the solution. Finally, the **complete reinjection of the geothermal fluid** can be pursued, avoiding the release of gases in the atmosphere, and guaranteeing the preservation of the resource.

Binary plants in general, and Organic Rankine Cycles in particular, have a very flexible design structure, where many components can be considered or not, according to the specific features of the project, in order to maximize the conversion efficiency, the economic gain, the O&M activities or a mixture of these. It can be easily understood that, thanks to such a flexible design, these power plants are suitable for working in a very wide range of boundary conditions. However, to exploit the possibilities triggered by this technology, only an appropriate know-how can effectively achieve the maximum satisfaction of the customer's requirement.

As a proof of these advantages towards a more sustainable exploitation of geothermal resources, against an installed capacity of about 25% of the overall 16 GW mentioned earlier, Binary ORC technology accounts for around 65% of the new installed power since 2015, underlining an important trend in the new most recent developments.

3. CASE STUDY: STATE OF THE ART

3.1 Geothermal Exploitation in the Philippines

The Philippines are the third country worldwide for electricity production from geothermal sources, with an installed capacity of almost 2000 MW and an average capacity factor close to 90%. Together with Indonesia, which is the second largest producer and has a similar amount of installed capacity, these are the only two relevant countries in the ASEAN region active in the geothermal power. Despite this, in the 2015-2020 period, only a 12 MW unit has been commissioned in the Philippines, indicating a lacking willingness to continue the segment expansion. However, from the end of 2020 a fresh wave of dynamism has started pervading the sector again, with new investments and an increased attention to the efficient exploitation of the existing resources. For the following five years it has been estimated for the Philippines a potential addition of almost 100 MW of new capacity, while the overall development potential exceeds 4 GW of installed power (Huttrer, 2020).

In both Indonesia and Philippines, **most of the existing power plants are single flash units**, as the one described before in section 2.3. Moreover, the majority of the reservoirs used are liquid-dominated type, meaning that most of the geothermal fluid is liquid, and it is reinjected hot, immediately after being separated. For this reason, the potential available from cooling down the reinjected brine in a binary plant is extremely attractive, since the source is not only assessed, but also already present and available. In this way, the resultant "**Brine Recovery**" application has all the advantages of the geothermal energy without the complexities linked to the source uncertainties or to the cost of drilling. In Figure 1 it is shown an example of possible retrofitted integration between a single flash cycle and a binary cycle, however there are many other ways in which their combination is possible.

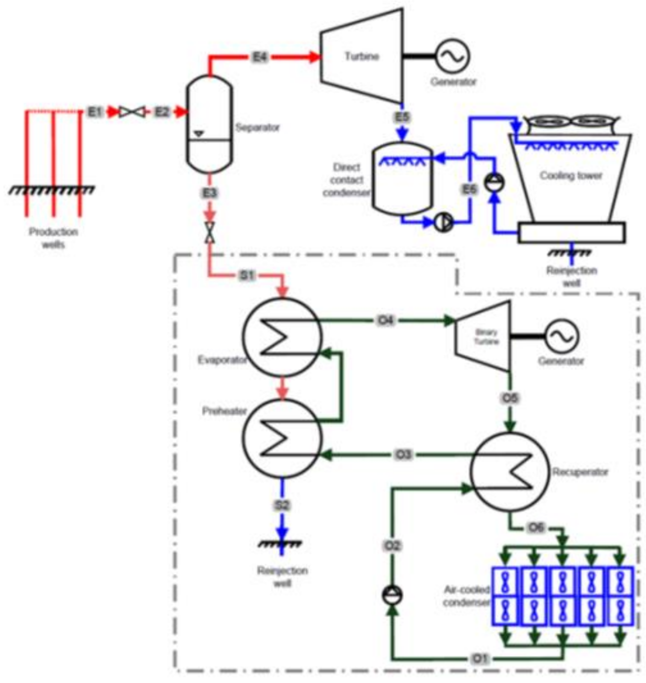

Figure 1: A simplified scheme of a retrofitted combined geothermal configuration, also called a brine recovery plant

3.2 EDC Existing Power Plants: Mindanao I and Mindanao II

With 45 years of history and more than 60% of the Philippines installed geothermal capacity, **Energy Development Corporation (EDC)** is one of the biggest geothermal operators worldwide and the most important in the Far East region. Among their 1477 MW of installed renewable capacity, 104 MW come from the Mindanao Geothermal field, located close to Mt. Apo in the Mindanao island. Here, two steam turbines of similar size have been producing electricity from **single flash cycles** since the last years of the previous millennium. With respect to the **Fehler! Verweisquelle konnte nicht gefunden werden.**, after both turbines there is an indirect water-cooled condenser, coupled with the cooling towers. In this way, against a slightly higher investment cost, there is the possibility to use the steam condensate for many different uses, and only a part of it as make-up water for the cooling towers. The first 52 MW unit has been commissioned in 1997, while the second one started its activity in 1999. The reservoir system can rely upon 23 production and 7 reinjection wells, relatively to a liquid dominated hydrothermal system. After an initial decrease in the well enthalpy of the order of -8% occurred during the first years of operation, the reservoir behavior has always remained constant. However, the huge amount of brine reinjected without using it at all, in the new scenario of optimization of the available sources, has lit the possibility to **increase the productivity of the geothermal field** using a small amount of the hot brine.

Figure 2: Mindanao I and Mindanao II geothermal power plants

4. MINDANAO III: EXERGY'S CUSTOMISED ORC SOLUTION

4.1 Exergy International: an ORC company with a deep know-how in geothermal power generation

Exergy International srl is the **worldwide developer, engineer and producer of Organic Rankine Cycle** systems, with the innovative Radial Outflow Turbine technology. ORC systems are used for power production from renewable energy sources including geothermal, biomass and concentrated solar power as well as from waste heat. The ORC is the best solution when the enthalpy level of the heat source is low, or if the size of the application is too small for a steam power plant to be an efficient solution. The plant configuration and thermodynamic principles at its basis are the same, but the ORC advantages are based on the differing thermodynamic properties of the single organic fluid. The fluid is chosen to best fit the heat source, thus obtaining higher efficiencies.

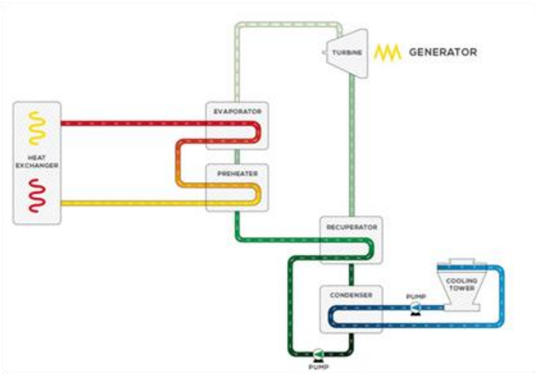

Figure 3: Simplified diagram of a water-cooled Organic Rankine Cycle, with heat delivered from an intermediate circuit

The advantages of the ORC over the traditional Rankine cycle include:

- Suitable for lower temperature applications

- Low rotation and tip speed in the turbine, together with the absence of liquid in the low-pressure stages
- Phase during expansion lead to a reliable and long-lasting expander, with simple and low-cost maintenance
- Compact and automated, meaning no need for operators
- Design flexibility with the option to utilize the most efficient working fluid available
- Operational flexibility for superior off-design performances
- A no-water consumption option is possible
- High market availability of chemicals /fluids with refilling rarely required
- Low associated costs for foundation and assembly
- Simple and reliable system maintenance made for long product life

Having the unique advantage of operating under diverse conditions, ORC engines perform with greater efficiency and flexibility than traditional Rankine cycle technologies. Exergy undertakes the development and manufacturing process of the ORC turbine and plant internally. This includes in-house R&D, engineering, project management, testing and after-sales service, but Exergy also operate a central control room to provide remote monitoring of the plants of its Customers.

Activities are undertaken in a custom-built facility in Varese, to the north-east of Italy. The region is rich in valued partners and a skilled technical workforce due to the traditional presence of mechanical and turbine factories on the territory plus leading Universities and R&D centers. Inaugurated in 2013, the new facility ensures the engineering teamwork in proximity to the operations and assembly teams.

4.2 Exergy's core technology: the Radial Outflow Turbine

Designed by Exergy, the Radial Outflow Turbine (ROT) is an innovative technological breakthrough. This technology is covered by current and pending patents and is the first turbine of its kind to be utilized in an ORC system. The Radial Outflow Turbine, different from the axial and radial inflow configuration, can convert the energy contained in the fluid into mechanical power, with higher efficiency than any competing technology present on the market. In 2011 Exergy developed a supplementary Radial Axial configuration suitable for waste heat or biomass engines. The single disk Radial-Axial configuration offers maximum efficiency with an extreme volumetric ratio.

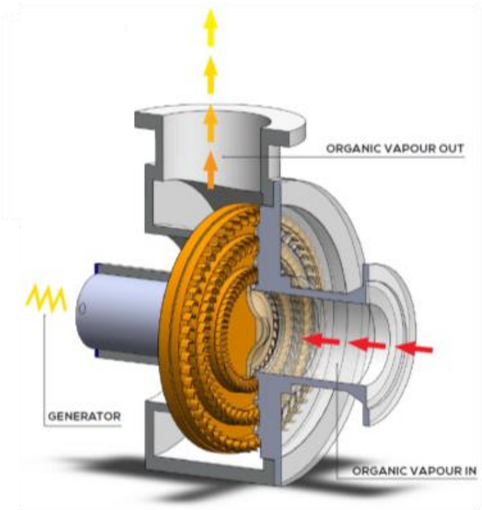

Figure 4: Exergy's Radial Outflow Turbine

When working with an organic fluid, most of the characteristics of the ROT become advantageous. For example:

- Higher efficiency than an axial turbine
- Multiple pressure admissions possible on a single disk
- Low speed turbine means no gearbox, and therefore higher reliability
- Large increase in volumetric flow achieved without the need for extreme changes in blade height
- Outward movement of fluid leading to minimum 3D effects
- Minimum turbulence, meaning maximum efficiency
- Excellent match between volumetric flow and the cross section across the radius
- No need for partial admission
- Lower tip leakage and disk friction losses
- Low vibrations, meaning longer life on the bearings

All these factors lead to a more compact and efficient machine, rotating at a low speed with minimal noise and vibration.

4.3 Exergy's ORC brine recovery design: Mindanao III

Exergy's Mindanao III ORC power plant is fueled by the brine coming from EDC's Mindanao I and Mindanao II power plants at the temperature of 140°C and, as it will be discussed in the following paragraph, cooled down to 80°C in the high alloy stainless-steel tubes of shell and tube heat exchangers. The ORC design has been conducted considering the following design conditions:

- Reference ambient wet bulb temperature: 17°C;
- Brine Pressure at ORC Inlet: 6 bar;
- Brine Temperature at ORC Inlet: 140°C;
- Brine Flow at ORC Inlet: 110 kg/s;
- NCG Mass fraction in brine flow: 0%;

The thermal power recovered from the brine is used to preheat and evaporate a flow of organic fluid typically used in ORC geothermal applications. This flow enters the Radial Outflow Turbine in saturated conditions and is expanded down to the condensation pressure. The condenser is an indirect shell and tube water-cooled condenser, with the cooling water coming from a cooling tower designed and supplied by Exergy just like all other key equipment. It is interesting to notice that the make-up water for this cooling tower comes from the geothermal steam condensed in Mindanao I and II power plants, highlighting a **further degree of integration between the flash and the ORC** units. After the condenser two feed-pumps are used to increase the pressure up to the maximum value, to close the loop. The redundancy grade of any element of this power plant has been evaluated in order to allow maximum rates of availability for all the lifetime of the plant, which is expected to work for more than 20 years.

Everything in this cycle has been optimized according to Exergy's know-how and experience. From the smaller details like the electrical wires, threatened by a H_2S rich environment, up to the most impacting equipment like the turbine, the generator, the cooling system, the heat exchangers or the acid dosing system, **each component deserved the attention of Exergy's engineering team**, that evaluated carefully all possible implications of any design choice in close cooperation with the engineering team of EDC. The power plant completed in less than 14 months started delivering its 3.6 MW of electric power to the grid in May 2022.

4.4 A critical aspect: the reinjection temperature

The reinjection temperature is a key parameter in the development of a geothermal project, and it can be the crucial factor in determining the success or the failure of the field.
From a purely theorical perspective, the more you cool down the heat source, the more heat you have available for the conversion of thermal energy into electricity, so the first approach will be to take all the thermal input that is possible. However, as a consequence of Carnot's Theorem, one of the most relevant in thermodynamics, the lower is the temperature of the hot source, the lower will be the conversion efficiency. In particular, considering cooling down the brine source from the initial temperature T_{in} to the outlet temperature T_{out}, the maximum conversion efficiency is limited by applying Lorenz's theorem to a trapezoidal cycle, and is according to the following formula:

$$\eta_{Trap,max} = 1 - \frac{\mathrm{Tamb}}{\frac{\mathrm{Tin-Tout}}{\ln\left(\frac{\mathrm{Tin}}{\mathrm{Tout}}\right)}} = 1 - \frac{\mathrm{Tamb}}{\mathrm{Tml,H}} \tag{1}$$

Where T_{amb} is the ambient temperature, $\eta_{Trap,max}$ is the maximum efficiency achievable ideally from a trapezoidal cycle, while the denominator ($T_{ml,H}$) is the mean logarithmic temperature of the hot source (which has nothing to do with the Logarithmic Mean Temperature Difference – or LMTD – used commonly in heat transfer). In other words, Lorenz generalizes Carnot's theorem for hot sources at variable temperature, while for constant temperature sources (i.e. T_{in}=T_{out}=T_{hot}) they converge to the same result.

It is now clear that the lower is the reinjection temperature, the lower the hot source logarithmic temperature and thus the lower will be the power cycle conversion efficiency. As an example, in the picture below it is possible to understand how decreasing the brine outlet temperature, the thermal power available from a hot source increases (at T_{in}=150°C), while the maximum theorical conversion efficiency (alias Lorenz efficiency) decreases. Consequently, the electrical power, calculated as the product between these two factors, has a maximum (at around 40°C in Figure 5); any further decrease in the brine reinjection temperature results in a lower electrical output.

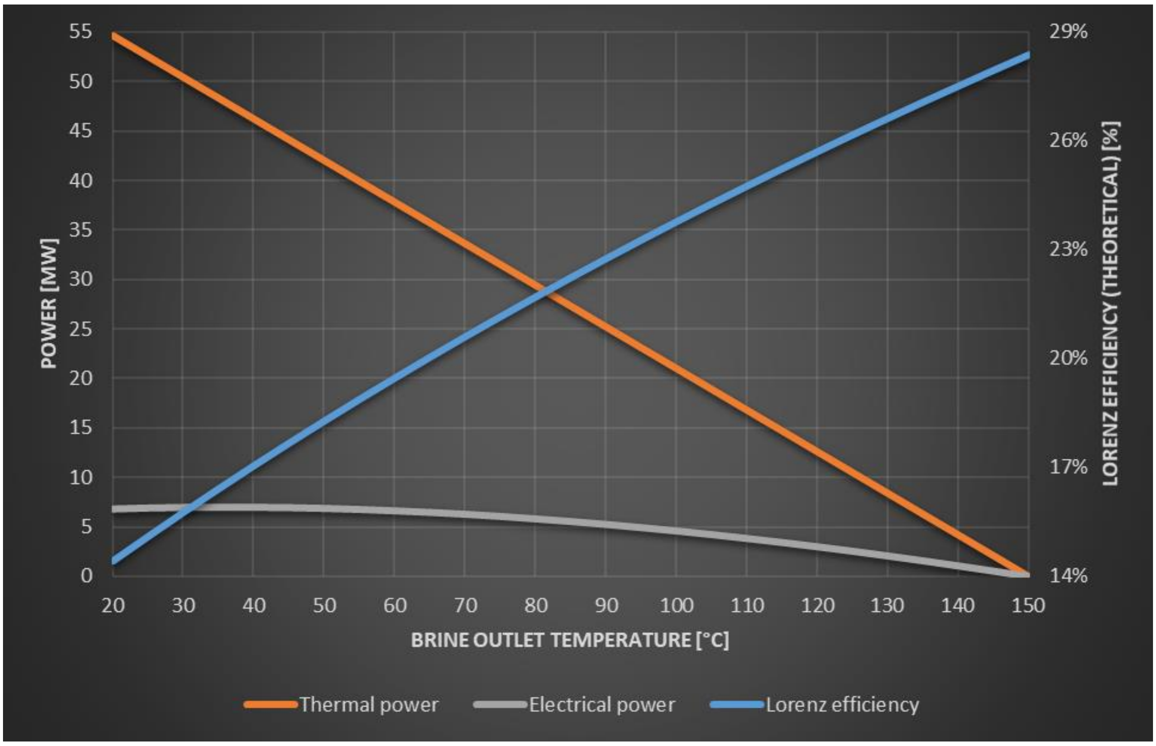

Figure 5: Relationship between brine outlet temperature, thermal power available, Lorenz conversion efficiency and maximum electrical power output available from a brine source at 150°C

Moreover, many differences occur from a practical point of view that are not considered in the simplified analysis above. As an example, there is a difference between the condensation temperature of the cycle and the ambient temperature, and between the resource and the evaporation, due to the fact that the surface of the condenser is not infinite. The presence of these effects pushes upwards the outlet temperature at which we have the maximum electrical power. Finally, there are also some technoeconomic considerations so that, unless the price of electricity is very high, the most cost-effective solution will have an optimal reinjection temperature which will be slightly higher than the technical optimum.

Nevertheless, when considering brine recovery geothermal projects, where a flash turbine is present after a separator, such as Mindanao III, the most relevant factor to be accounted for is the deposition of solid substances. This phenomenon called "scaling", can involve many different chemical species, but is particularly relevant in case of silica scaling (but also calcite can be relevant), since once occurred it is almost impossible to solve it and makes it very tough to deal with it. The silica deposition happens because of several chemical processes that occur simultaneously in the geothermal resource. These are monomeric silica polymerization, co-precipitation with other minerals and ions (predominantly with metals as Fe or Al) and direct deposition of monomeric silica (Gill and Jacobs, 2018). To explain why scaling happens, a very effective similitude is the one of sugar in the cup of coffee: when it is hot, you can add a lot of sugar, and up to a certain threshold, called the solubility limit, it will disappear. However, if you don't drink your coffee soon, it will cool down and some sugar will appear again at the bottom of the cup. This is because the solubility limit depends strongly on the temperature of the liquid, and when the temperature decreases, also the capacity of the coffee to keep the sugar in a homogeneous solution drops down. Silicates are typically present in geothermal brine, and as almost all solid particles, once flashed remain concentrated in the liquid phase. The silica deposition is affected by several factors which include chemical and physical composition of brine, temperature (Setiawan et al., 2019), acidity (Addison et al., 2015) and others. A hotter brine temperature results in a higher silica saturation in the disposal brine, which could cause a greater silica scaling precipitation in piping, heat exchangers, reinjection wells and other production facilities (DiPippo,1985).So, when cooling down the brine to recover heat for the ORC cycle, if scaling has not been considered carefully, it is possible that amorphous silica or other chemical component deposit in the shell and tube heat exchangers, jeopardizing the heat exchange process. Silica and quartz reach the equilibrium condition when the hot source is underground. When the mixtures, which are in two-phase condition, are carried up to the surface, the amorphous silica is supersaturated in the solution, thanks to the difference in the solubility of quartz and amorphous silica. The difference in the solubility is due to the flash that occurs when the mixtures are brought to the surface. So, the amorphous silica is the form of precipitation which happens at the surface level (Brown,2011).

In Figure 6 the limit of silica saturation is represented against the water temperature; the higher the steam fraction that goes in the flash turbine, the more concentrated will the silica result in the brine.

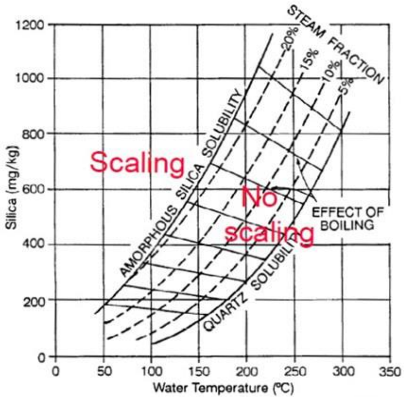

Figure 6: Solubility limit of silica in water

4.5 Exergy's solution: a customized acid dosing system

In the last decades, the focus has been moving from "IF" silica deposition happens to "WHEN" it materializes concretely. Even in presence of a supersaturated silica solution, there are some factors that can significantly delay the formation of scaling, solving such issue upfront. It is worth mentioning that the residence time of brine in the critical part of ORC heat exchangers and reinjection well is of the order of tens of seconds; for this reason, a system that delays silica deposition of half an hour allows to completely avoid any kind of issue. Brown (2011) suggests several solutions to deal with silica scaling. In the geothermal world the modification of the pH could be the largest use. At normal pH the polymerization of the silica is very rapid, while a pH about 5 can delay this phenomenon.

Numerical simulations and then experimental tests are essential for a proper selection of the main features of the dosing system. Silica scaling is a crucial aspect to monitor in a brine recovery power plant, so it is always suggested to carry out several chemical and physical analyses on the brine, also after the binary plant is in operation. These tests will allow to understand the brine behavior along the heat exchangers and in the reinjection well and will allow to optimize the design of the acid dosing system, suitable for each brine recovery plant.

Among the different possibilities that can inhibit silica scaling, for Mindanao III plant, Exergy focused on an acid dosing system. It is demonstrated in many different studies and applications, that low (acid) or high (alkaline) pH values are one of the most effective system able to achieve such objective. However, acid substances are preferred to alkaline ones, even though steel corrosion is not an issue with alkaline dosing, because of the much smaller operating costs that in the long run are extremely impacting. For this reason, a customized system has been studied, in order to achieve the targeted reinjection temperature (80°C) in the best possible way, keeping in mind all relevant issues that EDC, as a final customer, would experience in the operation of the plant.

Among the many decisions that have been made by Exergy's engineering team during the development of the inhibitor system, the most important are related to the kind of acid (strong vs weak), to the material selection, to the system and process arrangement, to the redundancy of the components and to the positioning of the system itself. Since these kinds of systems are not very widespread yet, each choice considered all possible working conditions without the possibility to rely upon a dominant technical paradigm.

For this type of application, is strongly suggested a chemistry analysis of the brine to avoid any type of scaling. The chemistry analysis must be conducted to analyze the pH and the chemistry composition of the brine in order to design the pH and the mass flow rate of the acid required to add to the hot brine for the specific case. The design of the acid dosing system requires a lot of test. For Mindanao III the acid dosing system has been dimensioned to have a pH equal to 4.5 at the re-injection temperature of 80°C.

Furthermore, to avoid scaling in the reinjection well, even when the ORC is stopped, the dosing system is designed to continuously work for about 4 hours to avoid any scaling problem in the reinjection well.

4.6 Exergy's Mindanao Power Plant Start up

The Mindanao III brine recovery binary plant was successfully synchronized to the Mindanao electricity grid on March 12, 2022 then passed compliance testing by system operator National Grid Corporation of the Philippines on March 25 and it is now delivering 3.6 MW of carbon-free electricity to the grid. Figure 9 is a picture of the completed power plant.

Figure 9: A picture of the Mindanao III brine recovery power plant

5. CONCLUSIONS

In a scenario of increasing energy demand, pushed by population and economic growth, Mindanao III geothermal plant could be the first of a long series of binary Organic Rankin Cycle bottoming flash units, extremely diffused in different areas worldwide and already present. This "Brine Recovery" trend would overcome one of the most crucial issues of the geothermal plants, the uncertainty of the source since it would exploit the wasted flows of brine already existing and available that is reinjected at high temperature. So, also the risks related to the initial investments are reduced. Another obstacle addressed and solved by Exergy's and EDC's engineering teams is linked to the reinjection temperature optimization and consequent silica deposition. Also, this issue in the past contributed to the technical selection in the development of many geothermal projects, but now the maturity of this technology has reached a turning point and is ready to be employed anywhere it is required.

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