MAKE USE OF GEOTHERMAL BRINE IN INDONESIA - BINARY DEMONSTRATION POWER PLANT LAHENDONG/PANGOLOMBIAN

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ABSTRACT

In order to successfully demonstrate geothermal binary power plant technology at an Indonesian site, a technical plant concept has been developed that complies with different requirements. The binary plant should use a quite small temperature difference in order to avoid scaling and preserve the possibility of hot reinjection. It should be possible to integrate a fully automatic binary plant at an already existing, predominantly manually operated geothermal field. And furthermore components from both, German and Indonesian suppliers should be used. Within this paper the design concept is explained and operational data and experiences are shared.

1. INTRODUCTION

Indonesia is known for its tremendous geothermal potential of around 29 GW_e which is dominated by wet steam fields. The currently installed capacity amounts to 2 GW from 15 areas (Darma 2016, Richter 2018a) still leaving huge part of the geothermal potential untapped. The prevailing plant type in Indonesia is currently the single-flash which directly uses the vapor part from the produced vapor-liquid-mixture to drive the turbine. Binary plants which transfer the geothermal heat to a separate working fluid are not yet an established technology at Indonesian sites. The first commercial binary units have been commissioned at Sarulla field in North Sumatra just in 2017 (Wolf & Gabbay 2015, Richter 2018b). Due to their adaptability they could however be implemented at much more sites and help to increase the geothermal capacity in Indonesia.

In order to successfully demonstrate geothermal binary power plant technology at an Indonesian site and to intensify the know-how transfer in this technology field a German-Indonesian collaboration project has been initiated in 2013 involving GFZ Potsdam (Germany), the Agency for the Assessment and Application of Technology in Indonesia (BPPT) and PT Pertamina Geothermal Energy (PGE).

The demonstration plant is located in the Lahendong geothermal area close to the village Pangolombian in the northern part of the island Sulawesi. The on-site construction phase of the demonstration plant rated with a capacity of 500 kW started in 2015 (Frick et al. 2015). Technical concept, component specification, coordination and supervision of detail planning, construction and commissioning were executed by the project consortium under guidance of GFZ. The operational phase commenced in September 2017. In January 2019 the demonstration plant was handed over to the Indonesian consortium.

This paper describes the technical concept and summarizes the first operational experiences of the demonstration plant that has been integrated at an already existing geothermal site.

2. STATE OF KNOWLEDGE

Figure 1 shows different types of integration for typical geothermal binary plants. About 20 % of today's binary plants complement the direct steam use at a geothermal high enthalpy site (Figure 1, left). In case of produced wet steam, the liquid phase from the separator can be used as heat source. But it is also possible to utilize the waste heat from the direct-steam turbine for driving a binary cycle. About 35 % of the installed geothermal binary plants use the complete fluid flow from a geothermal high- or medium-enthalpy field (Figure 1, middle). In most cases, steam and liquid phase are separated and used for evaporation and preheating, respectively. The remaining 45 % of the geothermal binary plants use hydrothermal systems (Figure 1, right).
When realizing binary power plants, different technical decisions have to be made. Important topics are working fluid selection and process layout but also turbine and heat exchanger design (e.g. Lakew & Bolland 2010, Maraver et al. 2014, Toffolo et al. 2014, Walraven et al. 2014). The thermodynamic analysis only is not sufficient when designing a binary power plant, also a techno-economic evaluation based on different criteria is necessary. Different approaches of techno-economic evaluation are presented and discussed e.g. by Hettiarachchi et al. 2007, Quoilin 2011, Shengjun et al. 2011, Cataldo et al. 2014, Li et al. 2014 and Astolfi 2014.
When realizing geothermal binary power plants also site-specific constraints, especially related to use of the geothermal fluid, are important. Reported constraints to realize a reliably operating plant are temperature limits of the geothermal fluid in order to avoid scaling, material aspects regarding corrosion (Franco 2011, Bronicki 2013, Wendt & Mines 2010) or to realize hot reinjection in terms of reservoir management (Noorolahi & Itoi 2011).
This paper addresses another aspect of reliable site integration and flexible use of a geothermal binary power plant. By using an intermediate hot water cycle it was possible to realize a fully-automated binary plant concept with flexible operation in an existing, predominantly manually operated geothermal field.

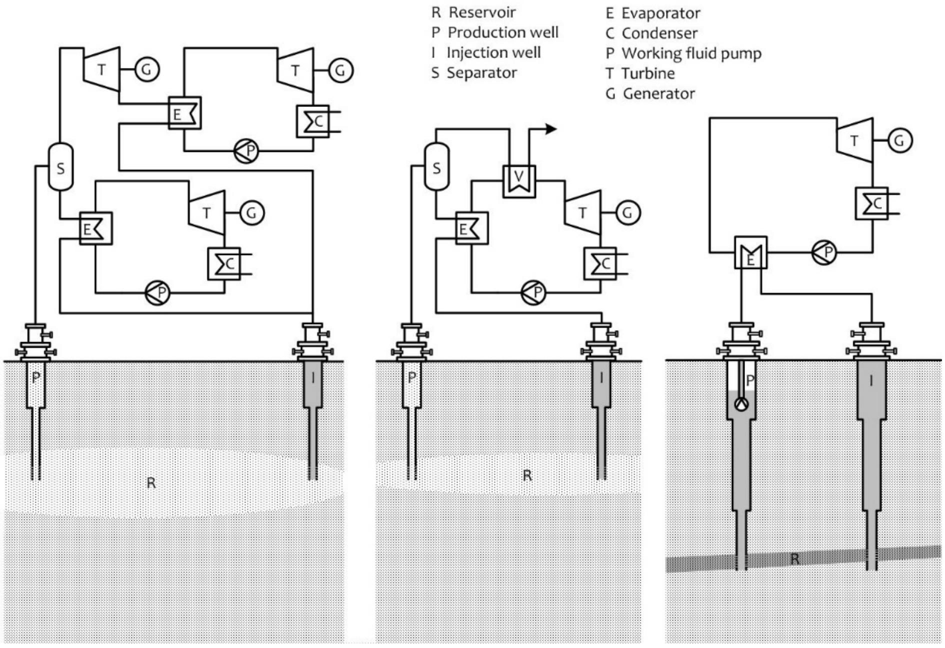

Figure 1: Site integration of geothermal power plants

3. TECHNICAL CONCEPT AND DESIGN DATA

The demonstration plant has been integrated at the Lahendong geothermal field close to the village Pangolombian where geothermal brine with a temperature of about 170°C corresponding to a separator pressure of 7.9 bar_a was available. The cool down of the brine should be limited to 140°C in order to have the possibility for hot brine reinjection close to the production well. Based on the available project budget the electrical capacity was rated with 500 kW so that the necessary brine flow rate was estimated with 30 to 35 kg/s. Cooling water was not available.

In order to meet the different site but also project specific constraints, it was decided to integrate a power conversion cycle by using intermediary closed water cycles for heat supply and heat removal. In terms of high reliability, the power conversion cycle was chosen to be a subcritical, single-stage Organic Rankine Cycle (ORC) with internal heat recovery. As working fluid n-Pentane, a well-known working fluid suitable to the heat source temperature was selected.

The process diagram is shown in Figure 2. Solid lines indicated normal operation. Dotted lines indicate operation during start-up or shut-down of the demonstration plant.

During normal operation, the heat of the brine is transferred to the hot water cycle in the primary heat exchanger. The hot water is then used to heat up and evaporate the working fluid in the ORC preheater and evaporator. The hot water is continuously circulated and the pressure in the hot water cycle is maintained by means of an expansion vessel with nitrogen cushion.

In the ORC-unit the working fluid steam drives the turbine-generator-unit. After the turbine, the superheated working fluid steam is flowing through a recuperator register before getting in touch with the water-cooled condenser tubes. The heat removal in the cooling water cycle is realized with a dry cooler consisting of 6 units.

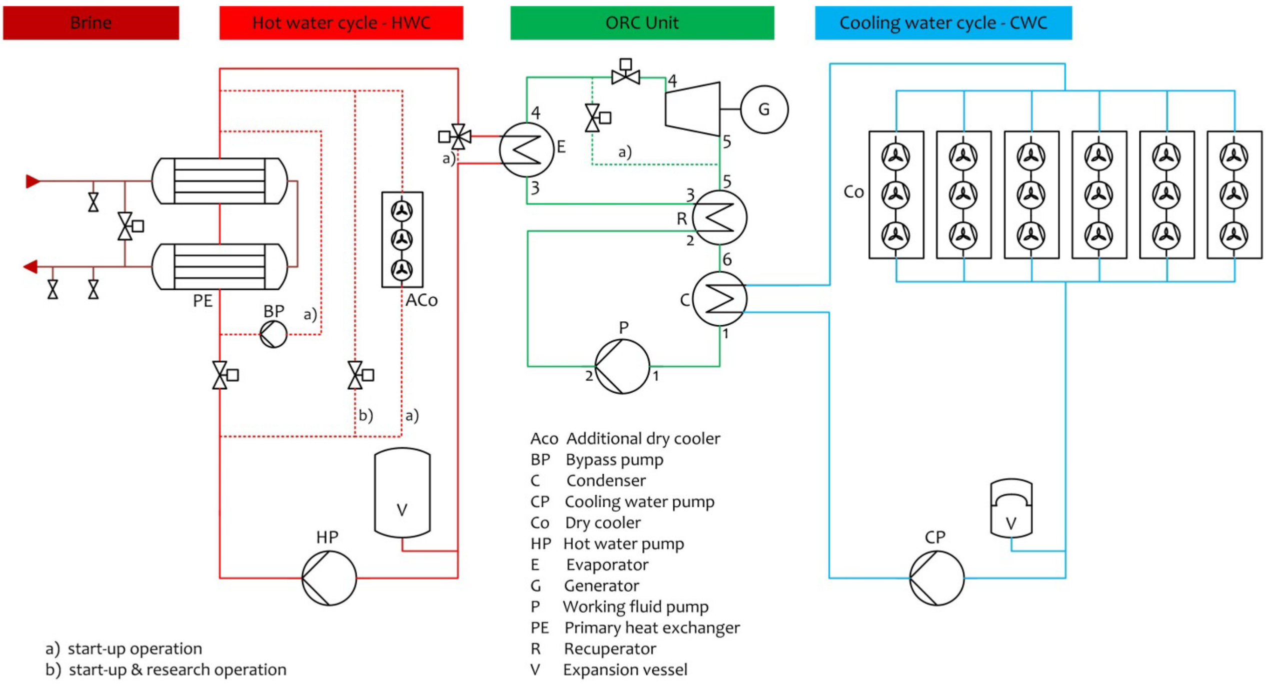

Figure 2: Flow Diagram of the demonstration power plant

Using intermediary water cycles, the net power output is decreased due to additional heat resistance and additional power consumption of the pumps. The net power loss due to the hot water cycle has been estimated with about 13 % and the loss due to the cooling water cycle with about 11 %. However, in this project the intermediary water cycles were realized due to design, installation and operational advantages.

Using a hot water and a cooling water cycle, it was possible to transport and install a completely preassembled and pretested ORC-unit. Using the hot water cycle, it was further possible to operate, shut-down and start-up the binary plant without changing the existing operational regime of the brine supply. The additional dry cooler realizes the start-up conditions for the prototype ORC-unit, which needs supply temperatures lower than 70°C. The controlled valves realize a defined temperature ramp during start up and enable to control the ORC supply temperature.

The hot water by-pass pump is implemented to realize modest temperature differences around the primary heat exchanger during plant restart and brine system start-up in order to reduce thermal stress and reduce the risk of steam hammer on the brine side.

Another advantage of the hot water cycle is the different design priorities for the heat exchanger that can be realized. For the primary heat exchanger transferring the heat from the brine to the hot water, the accessibility of the tubes for cleaning procedures and corrosion resistant materials have a high priority. The evaporator design can focus on heat transfer since there are less constructive restrictions.

An advantage of implementing the cooling water cycle was that the design and operation of the dry cooler becomes much easier due to the well-known single phase heat-transfer of water. Furthermore, less working fluid was needed to fill the ORC-cycle and the risk of n-pentane leakage could be decreased.

The 3D-layout is shown in Figure 3

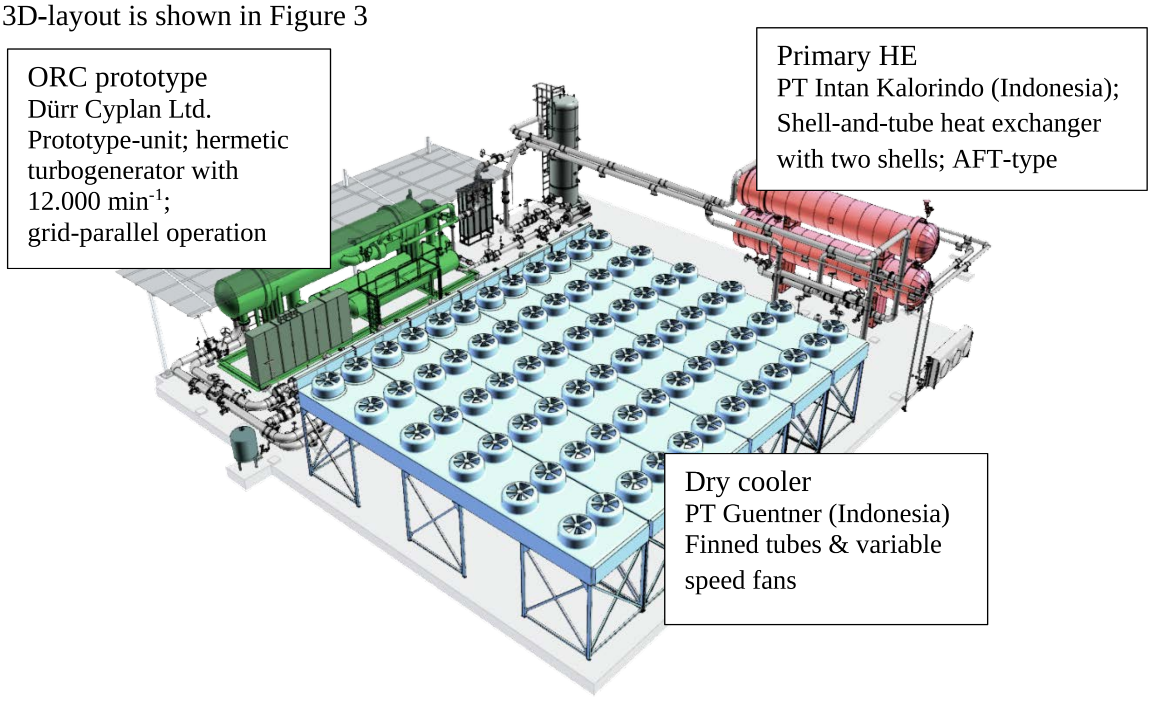

Figure 3: 3D-Plant layout

The main design data are listed in Table 1. For the geothermal fluid supply, a design mass flow $\dot{m}_{geo}$ of 32 kg/s was considered. Supply and return temperature $T_{geo,i}$ and $T_{geo,o}$ of the geothermal liquid were assigned with 170°C and 140°C, respectively. The heat capacity rate of the hot water was adapted to the heat capacity rate of the geothermal fluid in order to minimize the exergy destruction in the primary heat exchanger. Based on economic considerations the minimum temperature difference between geothermal fluid and hot water was set with 5 K.

Due to the small temperature change of the brine during heat supply, the process design of the ORC-unit had to be adapted accordingly. Since the evaporation temperature delivering the maximum power

output would lead to a hot water outlet temperature lower than 135°C also resulting in brine return temperatures lower than 140°C. Therefore the outlet temperature and not the power output was decisive for the selection of the evaporation temperature and pressure.
The condensation temperature of the ORC-unit was selected based on the maximum net power output considering the power consumption of all components, also the cooling water pump and the dry cooler fans. Since a lower condensation temperature leads to a higher gross power output but also higher fan power consumption, an optimum condensation temperature exists yielding the maximum net power output for a given dry cooler size. Based on economic considerations, the dry cooler cross-flow section was defined with 120 m^2. The cooling water temperature spread ΔT_{CW} was also selected based on economic deliberations.

Table 1: Design data of the demonstration plant

	Temperatures		Mass flow rates		Electrical power	
Brine supply	$T_{geo,i}$ °C $T_{geo,o}$ °C	170 140	$\dot{m}_{geo}$ in kg/s	32		
Hot water cycle	$T_{HW,i}$ in °C $T_{HW,o}$ in °C	165 135	$\dot{m}_{HW}$ in kg/s	32	$P_{el,HP}$ in kW	8.9
Cooling water cycle	$T_{a,i}$ in °C $T_{a,o}$ in °C	25.0 40.7	$\dot{m}_{a}$ in kg/s	221.4	$P_{el,Co}$ in kW	25.4
	$T_{CW,i}$ in °C $T_{CW,o}$ in °C	34.0 44.0	$\dot{m}_{CW}$ in kg/s	86.1	$P_{el,CP}$ in kW	16.2
ORC-unit	T_{ev} in °C T_{Cd} in °C	142.6 49.4	$\dot{m}_{WF}$ in kg/s	9.5	$P_{el,G}$ in kW $P_{el,P}$ in kW	499.4 23.4
Net power					$P_{el,Net}$ in kW	425.5

4. EXPERIENCES AND PLANT OPERATION

The geothermal binary demonstration plant is successfully operating since September 2017 and has produced more than 1.6 GWh gross electricity and 1.3 GWh net electricity until April 2019. Since the commissioning, several technical modifications have been realized in order to improve the plant reliability and availability under the given site conditions. Besides adaptations accounting for the high ambient humidity, modifications of the prototype-turbogenerator, the hot water cycle and the plant control were necessary in order to adapt to the many starts and stops of the plant due to the availability of the electrical grid (mainly power outages, phase failure) and problems of the grid connection. The binary plant has been designed for grid-parallel operation and is not capable for electrical island mode operation. Since September 2017 the plant has experienced more than 130 plant stops and starts. Also the real brine conditions made it necessary to modify some operating procedures. Instead of pure liquid, as assumed for the design, a two-phase flow is supplied to the binary plant. Both, the well conditions and the operation regime of the separator have changed since the start of the project.
At the moment, the plant is operating with reduced power in order to supply the geothermal injection pumps nearby. In *Figure 4 - Figure 6* plant data representing typical operation are presented and are compared to modelled operating values. Due to the operation at off-design conditions, the maximum proven gross power until now is 400 kW.
It can be seen that the heat supply is constant over the shown 48 hours period (constant hot water temperatures and volume flow) and that the hot water supply temperature $T_{HW,I}$ is reduced since not the full hot water volume is flowing through the primary heat exchanger and a part is flowing through the

bypass (*Figure 4* left and *Figure 5* right). In *Figure 4* right the temperatures and pressures of the brine supply are shown in relation to the saturation pressure of water. It can be seen that the supply pressure is very close to the saturation pressure and that the cool down of the brine is very small, both facts indicating two-phase flow at the inlet and liquid flow at the outlet of the primary heat exchanger. Most of the extracted heat is based on condensing the vapor phase in the brine supply.

In *Figure 5* left the course of the ambient and the cooling water temperatures are shown. The ambient temperature varies between day and night in the range between 30°C and 20°C. In the shown operating regime, the cooling water supply temperature can be kept constant until an ambient temperature of about 27°C by means of variable speed fan operation. For higher ambient temperatures 100 % fan capacity is reached and the cooling water supply temperature follows the course of the ambient temperature. The cooling water volume flow is controlled in order meet a specified cooling water temperature spread. It can be seen that the set value was changed from 10 to 8 K within the shown operation period resulting in an increase in the cooling water volume flow (*Figure 5*).

In *Figure 6* the run of the gross power and the net power output are displayed. The gross power follows the course of the cooling water supply temperature with opposite effect since a higher cooling water temperature results in a higher condensation temperature (*Figure 5*) and hence a lower power output. The net power instead shows a strong relation to the ambient temperature course with higher ambient temperatures leading to larger fan power consumption and hence a lower net power output.

The numerical model that has been developed with EES (Engineering Equation Solver) comprises the hot water cycle, the ORC-unit and the cooling water cycle and uses the hot and cooling water supply parameters and input variables as well as the superheating of the working fluid vapor. For modeling of the heat exchangers, heat transfer and pressure loss correlations from the VDI heat atlas (VDI Gesellschaft 2010) have been used applying real geometry data. The turbogenerator is represented as a turbine wheel with upstream laval-nozzle stage. The isentropic turbine efficiency has been adapted based on operational data. Based on this data, the isentropic turbine efficiency is increasing with increasing pressure difference across the turbine and having a best performance point depending on pressure difference. The efficiency of the generator and the feed-in unit are assumed to be constant.

From *Figure 4*-*Figure 6* can be seen that the model is giving a good representation of the plant performance. Despite the gross power which is underestimated by about 3 %, all other values can be reproduced with good accuracy.

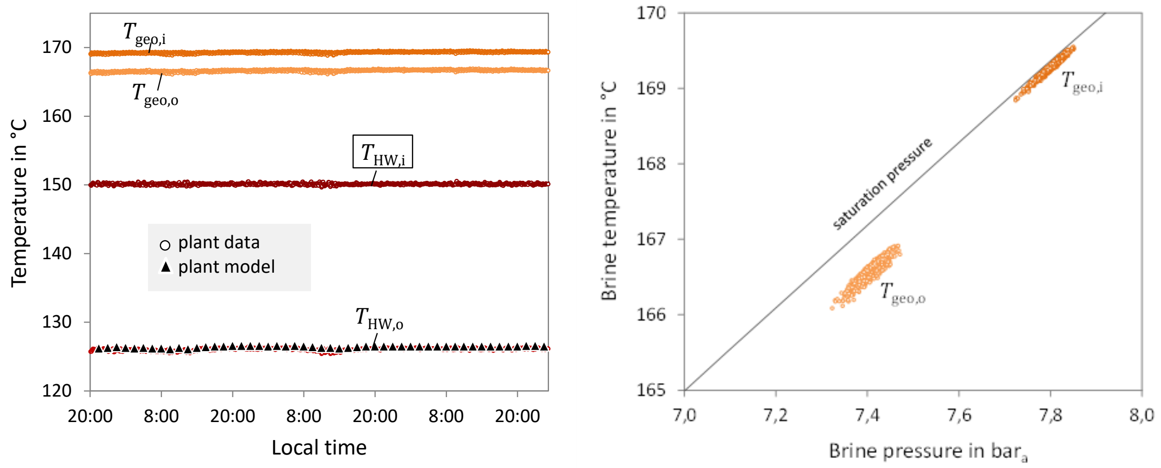

Figure 4: Plant data and modeled data for 48 hours operation – brine supply and hot water cycle temperatures (left) brine temperatures and pressures in relation to the saturation pressure of water (right)

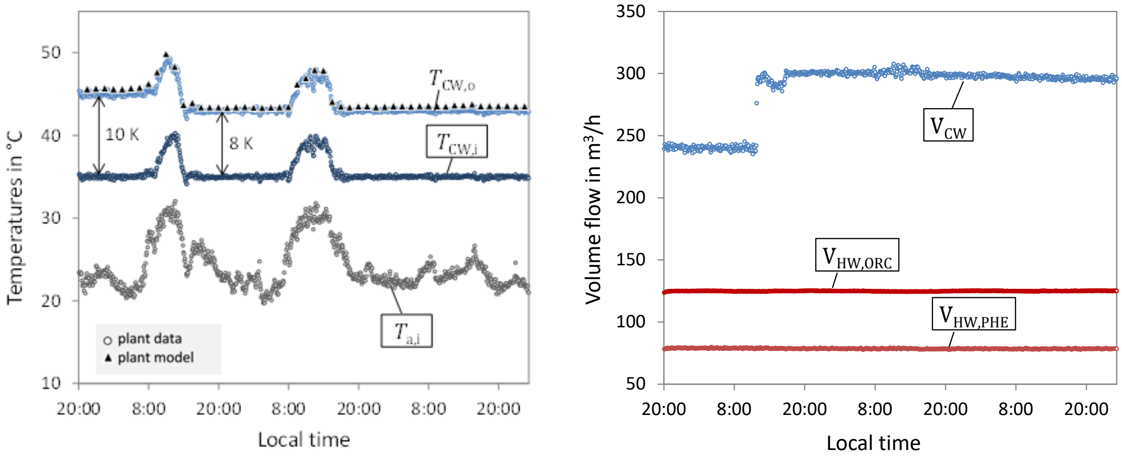

Figure 5: Plant data and modeled data for 48 hours operation – cooling water cycle and ambient temperatures $T_{a,i}$ (left), hot water volume flow in ORC ($\dot{V}_{HW,ORC}$), in PHE ($\dot{V}_{HW,PHE}$), cooling water volume flow ($\dot{V}_{CW}$) (right)

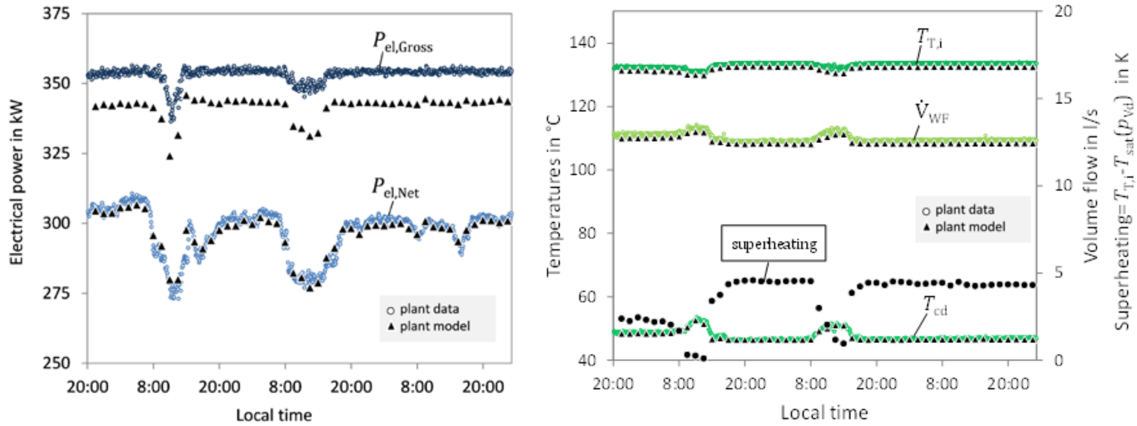

Figure 6: Plant data and modeled data for 48 hours operation – gross and net power output (left) process temperatures (turbine inlet $T_{T,i}$;condensate temperature T_{cd}) and volume flow rate ($\dot{V}_{WF}$) ORC-unit (right)

With the model, the power output of the binary demonstration plant can be estimated for varying hot water and cooling water temperatures. In Figure 7 the gross and net power output for a saturated steam cycle is shown. The net power reaches a maximum depending on the cooling water inlet temperature and increases with higher hot water temperatures.

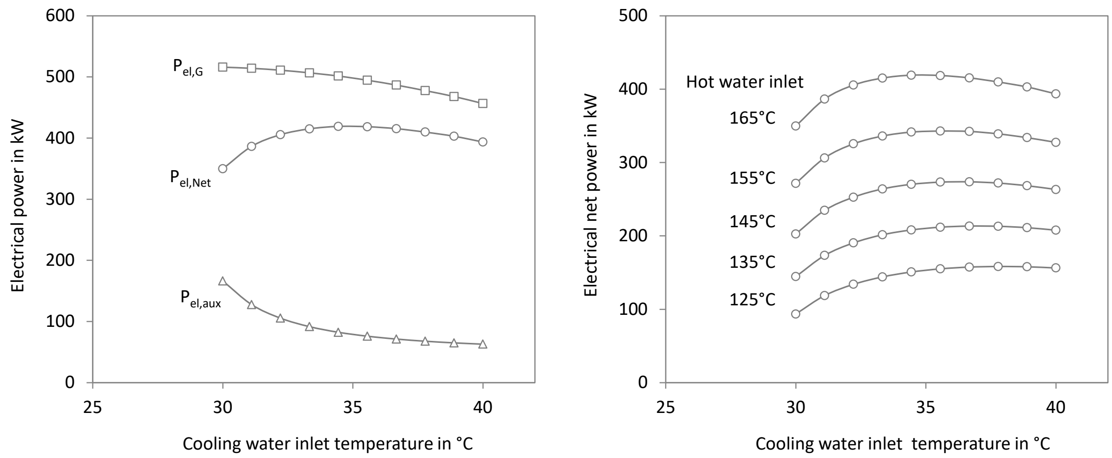

Figure 7: Estimated plant performance depending on the cooling water temperature for different hot water inlet temperatures ($T_{a,i}$=25°C)

5. CONCLUSION AND OUTLOOK

Due to the technical concept using intermediate cycles it was possible to integrate a fully automated binary plant and use components from both, German and Indonesian suppliers. Due to the intermediate hot water cycle it is also possible to operate the binary plant even though the brine conditions do not match the design conditions. Despite the design conditions (hot liquid) the binary plant is supplied with two-phase flow. It could be shown that full-automatic and grid-parallel grid operation is possible. However, most operational problems occur during plant stops and starts which are caused by power outages occurring much more often than expected in the planning phase.
The plant is currently operated with limited power output to meet the consumption of the injection pumps on site and because of the many sudden grid outages. Real plant data for typical operation where shown and an estimate of the power output depending on the hot water cycle temperature was presented.
In January 2019, the demonstration plant was handed over to the Indonesian consortium that is now operating and maintaining the plant. Besides commercial operation, the plant will also be used for demonstration activities and training. It is also planned to make technical improvements regarding the connection to the electrical grid in order to increase the plant availability.
The experiences and results from this demonstration project will be helpful for other projects. The experience shows that intermediate cycles, especially the hot water cycle without which the demonstration would not be operable, are interesting technical solutions. However, cost reduction potential should be evaluated.

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