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Turboden Geothermal References in Bavaria: Technology, Drivers and Operation

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ABSTRACT

The paper introduces the recent experience of Turboden with three 5 MW state of the art geothermal power plants in Bavaria, and the status of the operations.

A focus on the technology of these plants is made, particularly describing the type of thermodynamic cycle, the adopted scheme for district heating heat decoupling, the optimization drivers.

The importance of working fluid selection for optimized efficiency, and the selection of key components like heat exchangers and air-cooled condenser is highlighted.

The German frame regulation for incentive scheme and grid requirements are described, island mode operation are pointed-out and discussed.

Finally, the advantages of the adopted solution are summarized, together with the economic benefits in terms of enhanced energy production.

1. INTRODUCTION: TURBODEN GEOTHERMAL PLANTS IN BAVARIA

Turboden stands among the pioneers of Organic Rankine Cycle Technology (ORC), being at the same time a European Leader for biomass, heat recovery and Geothermal applications.

Currently there are more than 240 Turboden ORC plants in operation, featuring in-house designed turbines, and further 40 plants under construction. Turboden ORC units have demonstrated an average availability exceeding 98% and more than 5,000,000 operating hours have been reached.

Between 2012 and 2013, Turboden has successfully implemented a 5 MW geothermal power plant for the Munich Public Utilities Company SWM (in Sauerlach), and two other 5.6 MW plants in the same region for the leading company Hochtief Energy Management, now SPIE Group (in Dürrnhaar and Kirchstockach). As described in chapter 6, these power plants have already achieved thousands of operating hours, also exceeding the expected performances.

A fourth geothermal plant has been recently awarded in Bavaria to Turboden. The 4.1 MW cogenerative geothermal plant that will be installed in the city of Traunreut, will deliver, in addition to the electric power produced, up to 12 MW thermal power to the community.

Turboden has always looked at geothermal energy with great interest since its origin, starting from the plant in Zambia (1988) and Altheim, that is running continuously since 2001.

Turboden over 30 years’ experience in the construction of ORC turbogenerators made it possible to construct units with high performance as well as high reliability and availability, together with low maintenance and operational costs.

In the following table the main features of the plants delivered by Turboden in operation in Bavaria are presented.

Figure 1: Dürrnhaar geothermal plant

Figure 2: Sauerlach geothermal plant

Table 1: Plant statistics

Site	*Sauerlach*	*Duerrnhaar*	*Kirchstockach*
P gross kW	5000	5600	5600
P net kW	4500	5000	5000
Water inlet T °C	140	138	138
Water flow l/s	110	130	130
Design ambient T °C	7,4	8	8
Working Fluid	R-245fa	R-245fa	R-245fa
Cooling System	ACC	ACC	ACC

2. FRAME CONDITIONS OF GEOTHERMAL PROJECTS IN GERMANY

The incentive schemes of feed-in tariffs provided by the German Renewable Energy Sources Act (EEG) made possible the market introduction of renewable energy sources for electricity generation.

The basic principle of the EEG is that the operators of electricity grids are obliged to accept and give priority to electricity provided by renewable energy sources and to pay minimum prices stipulated by law for a 20-year period, Gassner (2010) [1].

The feed-in tariffs for geothermal power, which have only been valid since 2000, have not yet fulfilled market growth expectations.

For this reason, the tariffs were increased in these years.

The high drilling and water circulation risks and related costs, due to the very deep reservoirs, still represent in Germany a barrier to investment which has not yet been balanced out by the feed-in tariffs.

So far, the continued interest in mining claims, which are a prerequisite for developing a project, confirms the interest in geothermal power generation.

At the time of the bid and design of the three power-plants before presented, the feed-in tariff was 20 €-cents per kilowatt-hour for gross electrical output.

In addition, a heating-use bonus of 3 €-cents per kilowatt-hour was guaranteed when electricity generation was combined with delivery of heating energy.

As of June 2014, the heat-bonus has been integrated to an increased feed-in-tariff of 25 €- cents per kilowatt-hour, to be paid on the Gross Power, while the cost for the auxiliaries consumption was given by the market value, i.e. approximately the half of the feed in price. For obvious reasons, thermodynamic solutions that enhanced the Gross power with correspondingly higher auxiliary consumptions seemed to be suitable (e.g. Super Critical cycle). However, the expected inflation trend of the cost of the auxiliaries has always concerned the developers and driven the choice to optimized-net-power-cycles like the two level pressure implemented by Turboden.

3. THE TWO (DOUBLE) LEVEL PRESSURE CYCLE PRINCIPLE

In general, when a variable temperature source is available (geothermal water) and the economic frame conditions push towards the adoption of high heat exchanger surface, the adoption of technical solutions that allow to match the form of the heat release curve of the geothermal water with the heat absorption curve of the energy conversion cycle are convenient.

When a classic subcritical ORC cycle is selected the heat transfer curve has the typical shape represented in Fig 3 below.

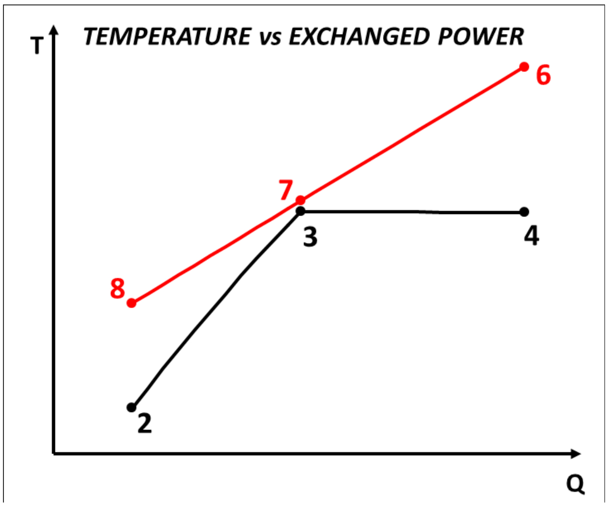

Figure 3: Temperature/Heat diagram of saturated single level cycle showing the pinch point

The presence of a minimum temperature difference point “pinch point” at the beginning of the working fluid evaporation does not allow an effective matching of the two curves. As a result, when the pinch point temperature difference (temperature difference between points 7 and 3 in Fig. 3) becomes small, the increase of heat exchange area becomes increasingly ineffective in terms of additional power that can be achieved.

For example, for a single level cycle with 245fa as working fluid with 2°C pinch point, operating on a geothermal water heat source at 150°C, the increase of the heat exchange area up to 250% of the original value would cause a power increase of less than 1%, Gassner (2010) [1].

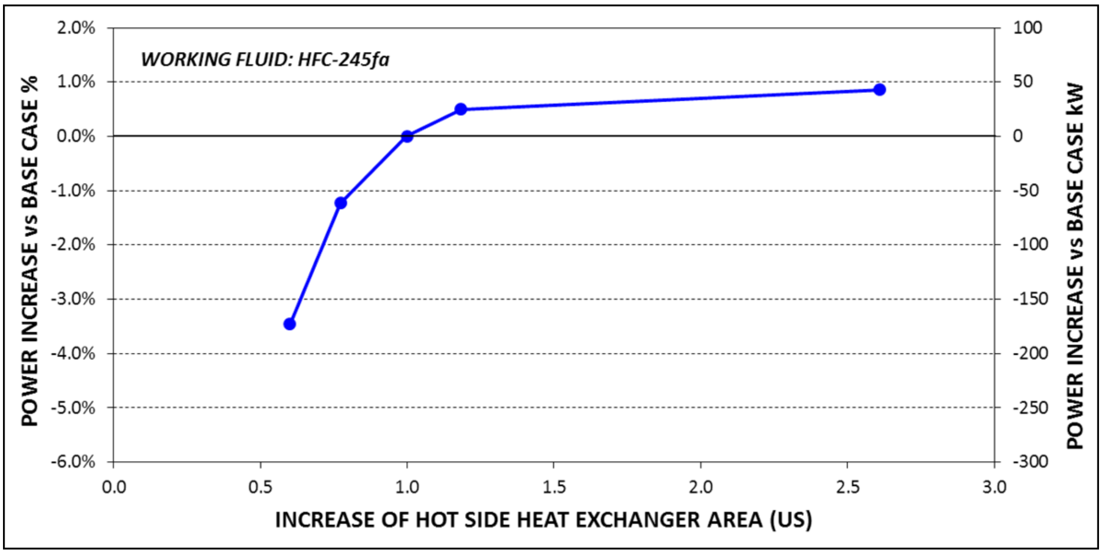

Figure 4: Influence of the heat exchange area on performance starting form a pinch point of 2°C according to, Gaia and Pietra (2013) [2].

In order to increase the power production with enhanced heat exchange area, the aforementioned power plants implemented by Turboden use two-evaporation pressure level cycles. With the input available at the plant locations (about 140°C) this solution allows a significant performance increase compared to a single level cycle assuming same heat exchange area.

In order to show the advantages of the two level cycle, a comparison has been made with two different single level cycles under typical German frame conditions. The cycles have been compared with same assumptions for component efficiencies and heat exchange coefficients comparing the required heat exchange surface and the achievable net power.

Main Assumptions:

Geothermal Fluid (liquid) temperature: 140°C

Condensing temperature: 20°C

Superheating: 2 °C

Turbine isentropic efficiency: 85%

Pump isentropic efficiency: 75%

A two-level cycle with HFC 245fa as working fluid and 3°C pinch point has been used as base case with 100% net power and 100% required heat exchange surface.

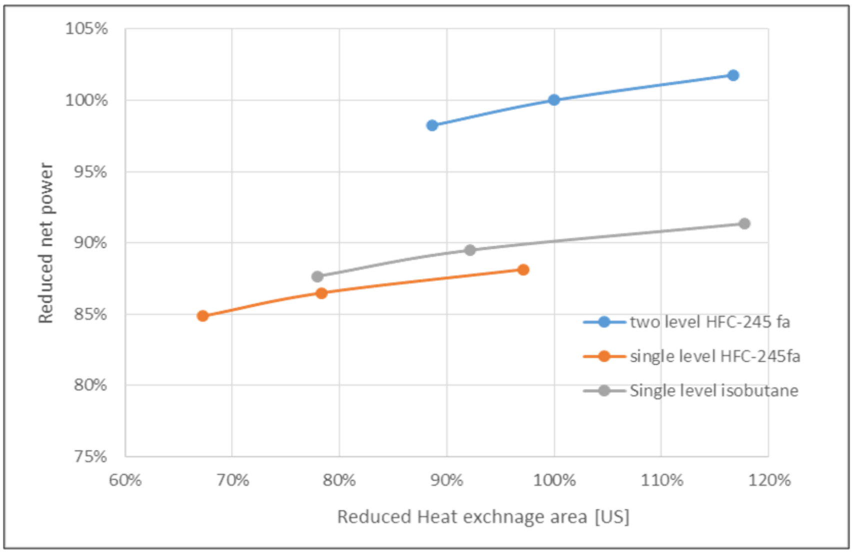

Figure 5: Comparison of two level cycle with saturated single level cycles for typical German frame conditions

The comparison shows that, with the above assumptions, about 10% additional net power can be produced with same hot heat exchange area compared to a saturated single level cycle.

Similar results can be obtained with a supercritical cycle where the matching of heat release curve is obtained thanks to the shape of the typical supercritical heat absorption curve with transition from liquid to vapor at variable temperature.

On order to simplify the cycle control and add redundancy to the system, the two pressure levels are conceived as two working fluid loops that are completely independent working fluid side, being only interconnected on geothermal water side.

The selection of the working fluid was based on the optimization analysis of the power production for a given value of heat exchange area and with careful estimation of turbo machinery efficiencies. In this comparison, the refrigerant R245-fa proved to be the most favorable solution mainly due to the following characteristics.

• Favorable heat absorption curve for a two level cycle fed with water at about 140°C

• Reduced enthalpy drop compared to hydrocarbons allowing for a particularly high turbine efficiency.

In addition, the fact that this working fluid is not flammable was positively evaluated by the customers - in particular for the Sauerlach plant close to inhabited area, where installation inside a building was required.

This solution implemented by Turboden has also the following additional technical advantages that are particularly important in German frame conditions.

3.1 Redundancy

The two working fluid loops are completely independent and therefore one loop can be operated also when the other cycle requires to be shut down for maintenance activities.

In case one of the turbines (say the high-temperature "HT" turbine) requires to be shut down, the whole unit will be shut down, and re-started in a very short time. In fact the electric generator is the only item connecting the two parts of the plant, and it can be disconnected quickly (operation sequence required: remove coupling cover, remove coupling bolts, re-install coupling cover, actuate valves, select turbine low-temperature "LT only' operation, re-start ORC). This operation would require about 1,5 hours, including re-start.

In addition to this, the overall energy production will be higher if the different loops are stopped for maintenance at different times because in "LT only" operation the low temperature cycle will benefit since the geothermal water is not cooled by the high temperature loop. Thanks to a suitable design of turbine and working fluid loop, and overdesign of the working fluid pumps, in "LT only" operation mode the plant can achieve a relevant overload compared to the nominal production of LT cycle.

3.2 Efficient heat decoupling

Another advantage compared to a single level cycle is the possibility to decouple and deliver heat for a heat user (e.g. district heating grid) with comparatively lower impact on the electric power production.

This is a key point under German frame conditions due to the following reasons:

• From environmental point of view, the saved carbon emissions are higher if the heat is used for heating purposes, due to the fact that the thermal efficiency for a geothermal heat source is up to10 times higher when it is used for heating (100 % thermal efficiency compared to 10 – 12 % electrical efficiency), while the same ratio is about 2 for fossil heat sources (roughly 80% thermal efficiency compared to roughly 40% electrical efficiency). Thus geothermal heat displaces much more fossil fuels if used for heating purposes.

• The economic value of the heat for electricity production is roughly 25 €/MWh if a feed in tariff of 250 €/MWh and a net electrical efficiency of 10% are considered. Economic value of heat is often 2 to 3 times higher, especially if used for district heating.

• While heat use is preferred from both environmental and economic point of view, suitable heat users are mostly available only for a limited number of hours per year (winter heating). Therefore combined plants with efficient and flexible heat decoupling are considered as very important. This is also the reason why the German legislation was providing for a "bonus for cogeneration", as indicated in chapter 2.

Compared to a single level cycle the two level cycle is particularly suitable for the decoupling of heat with comparative lower impact on the electric power production (see qualitative comparison of the different schemes in Fig. 6).

For example in the Sauerlach plant the net plant efficiency is about 11%. The HT loop has a net efficiency of about 12,5% while the LT loop has a net efficiency of about 7,5 %. The geothermal water leaves the high temperature loop at a temperature of about 90°C. Therefore the heat supply can be decoupled downstream of the high temperature loop, therefore subtracting manly the heat from the low temperature loop (i.e. the cycle with lower electric efficiency). As a result the energy loss when the heat is required for district heating will be significantly lower.

In order to show the advantages of the two level cycle from this point of view, the following simple calculation under realistic German frame conditions was performed. For the ORC cycle data typical values of the plants described in this paper were used.

Assumptions:

Net Efficiency HT cycle: 12,5%

Net Efficiency LT cycle: 7,5%

Net Efficiency ORC: 11%

Heat absorbed by LT cycle: 13500 kW

Brine temperature at ORC inlet: 140 °C

Brine temperature at inlet of LT cycle: 90°C

Brine temperature at ORC outlet: 45°C

District heating feed temperature: 80°C

District heating return temperature: 50 °C

Pinch Point district heating heat exchanger: 3°C

It is also assumed that the whole heat feeding the LT cycle can be delivered to a suitable heat user for 2000 h/year. This means that for this period the LT cycle will be stopped and only the HT cycle will operate. Consequently about 2000 MWh/year (calculated as lost heat input times ORC efficiency) of electric energy production will be lost.

With a single level cycle with same electrical efficiency, a part of the geothermal water would bypass the complete energy conversion cycle (ORC) for 2000 h/year. Hence, even without considering the impact of the reduced flow on cycle efficiency, at least 2650 MWh/year (calculated as lost heat input times ORC efficiency) would be lost. In fact, most probably the electricity production loss will be higher because the impact of the lower flow on ORC efficiency will not be negligible.

These additional advantages, have been a key point for the selection of the subcritical two pressure level solution instead of a supercritical single level cycle, that could have been an alternative way of reaching similar performances at nominal operating conditions.

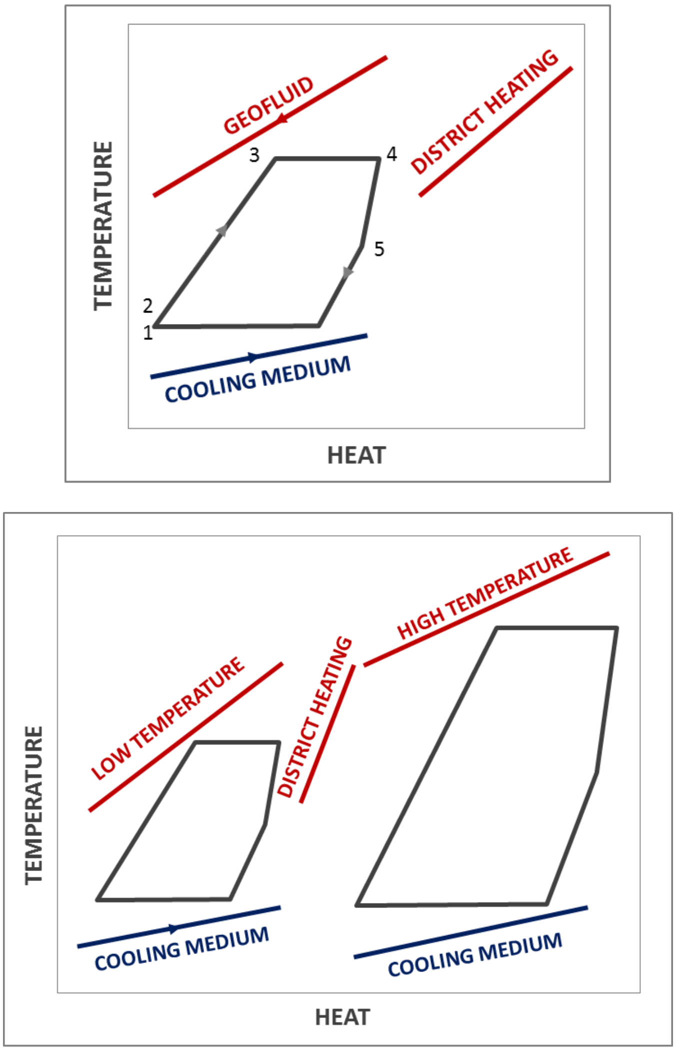

Figure 6: Comparison of single VS two level cycle for heat decoupling to district heating

4. POWER PLANT COMPONENTS

4.1 Heat Exchangers and pipelines

Heat exchangers have the function to transfer the thermal power from the geothermal water to the ORC working fluid.

Shell & Tube heat exchangers are used for both the HT and LT cycle. To avoid corrosion issues and increase durability of the heat exchangers, the material adopted for the parts in contact with geothermal water, is the super duplex stainless steel SAF2507 (e.g. tubesheet, distributor channel, partition plate and heat exchanger tubes).The material of the interconnecting pipeline between heat exchangers and Balance of Plant BoP, where the geothermal water flows, is 904L (1.4539) an austenitic stainless steel. On the ORC working fluid side traditional carbon steel is used for the heat exchangers shells and for most of the piping. Both HT and LT cycles are equipped with shut-off valves able to isolate any heat exchanger from the rest of the circuit (i.e. for maintenance operation). Shut-off valves are installed on geothermal water side and on the working fluid side. In this case only a small volume of the plant shall be drained during maintenance operation and the time spent to restore the plant in the normal configuration will be shorter.

4.2 Air Condenser

Part of the thermal power coming from the geothermal fluid is converted to mechanical power by the turbine, the remaining is dissipated by means of the air condenser. Many parameters can influence the design and the type of the air condenser, in these plants the main drivers that influenced the design have been: working fluid, own consumptions and noise level. In order to avoid leakage of working fluid (or inlet of air when the condensing pressure is lower than atmospheric pressure), all the main components of the air condenser are welded, and no flanges are present. A traditional configuration with plugs bonnet was discarded to adopt a solution with cylindrical welded bonnet. Also the interconnection nozzles between condenser and pipeline are welded. The tube to tubesheet connection is strength- welded, too. Free area available to install the air condenser, noise level allowed and power own consumption are linked parameters that in these plants influenced the choice of material of the fans, type of transmission and motors. (i.e. where the noise level allowed was low and the free area available for the ACC small, GFRP fans are installed). Tube bundles are made in carbon steel, the heat exchanging tubes are finned tubes; material of the fin is aluminum. Up to 35% of fans can be stopped, with the plant still running. The air condenser is composed by a large number of bundles interconnected each other in parallel mode. To limit the influences of different condensing pressure of the bundles (i.e. fans of one bay out of order), the pipeline, where the liquid phase is collected, foresees a routing with the presence of a syphon / vapor trap.

4.3 ORC feed pumps

Different configurations are adopted in these plants. The configuration able to guarantee the highest availability is the one present in geothermal power plant of Sauerlach. HT cycle and LT cycle are equipped with 2 pumps, completely redundant (2x100%), and in case of failure of the one pumps or other device and auxiliary connected to it, the control system is programmed to switch on the stand-by redundant pump without shutdown the ORC plant.

4.4 Drainage system

About 70 tons of working fluid is present in each plant. Cost and type of the working fluid influenced the design concept of the drainage system. As for the air condenser, the target was to limit the loss of working fluid during maintenance, without compromising the maintenance operation. The drainage circuit is able to guarantee to drain each volume of the ORC circuit independently by the others. For example, if the filter of the ORC feed pump is clogged, it is possible to maintain in operation the plant using the redundant pump, meanwhile it is possible to isolate the dirty filter from the rest of the circuit, drain the liquid phase and recover the vapor phase into the main tank, execute the cleaning operation and to restore the filter without to influence the operation of the plant and decrease of the availability. Drainage system installed consist of:

a) A tank/receiver with a volume sufficient to contain all the inventory of working fluid of the plant;

b) Two transfer items; a pump to move the liquid phase from the tank to the plant or vice-versa and a compressor, able to extract the vapor phase and to push it in a condenser where it is condensed and conveyed into the main tank;

c) Chiller circuit using R-134a as medium to condensate the vapor phase of HFC-245fa.

4.5 Auxiliary equipment

ORC plant is also composed from auxiliary components and circuits. If an auxiliary device is closely related to the normal operation of the plant, it shall be design in order to guarantee the highest availability. Auxiliary components closely related with normal operating condition are:

a) Lubrication circuits. Six different lubrication circuits are installed. High availability is guaranteed by redundant pumps and instrumentation installed on each circuit. Furthermore the configuration adopted guarantees to have a complete division between lubricant circuits required by the HT cycle and lubricant circuits required by LT cycle. Therefore in case of stop of one of the two cycles it is possible to re-start the plant with the required lubricant circuits only.

b) Auxiliary cooling system. It is a close circuit where a mixture of water and glycol is used, the system has the function to cool the electric generator and the lubricant oils of turbine and gearbox. Circuit is composed from: plate heat exchangers where the lubricant oils are cooled, two air cooler and two pumps. Like for lubricant circuits, where redundant pumps and instrumentation are installed to have an high availability, in this circuit also the air coolers are redundant. In fact in case of failure of one air cooler the second is able to dissipate the full thermal power by increasing the speed of the fans. The result is low own consumption during the normal operation and availability of the plant guaranteed in case of failure.

c) Non-condensable purging system. It monitors the presence of non-condensable gases (e.g. air) into the ORC circuit and in automatic mode it is able to purge them (inlet of air is possible during maintenance operation or in Winter when the condensing pressure is lower than atmospheric pressure); the result is a production of electricity always in according with relative design condensation pressure. In case of maintenance on the purging system the shutdown of the ORC plant is not required.

d) Instrumentation. To guarantee a high availability the instruments involved in main regulation loops (i.e. level, pressure) or main alarms are redundant and connected in different I/O boards of the PLC.

e) Distributed control system (DCS). The control system used is PCS7 and it manages and controls the whole plant. Redundant CPU and redundant servers are installed. The plant can be started-up and stopped in automatic and remote mode.

f) Transformers. Redundant step-up and step-down transformers are installed.

4.6 Island mode

For the geothermal power plant in Sauerlach, Island Mode operation was required by the bidding rules.

In case of failure of the grid the ORC plant is able to supply the power required by all auxiliaries (included the geothermal water pump), thus maintaining the plant in operation. The Island Mode has been successfully implemented and tested thanks to fast turbine admission valves, that can finely regulate the power output and mitigate the over-speed peak of the turbine (at grid failure) . Island mode presents a list of advantages, the main are:

a) Whole plant is maintained in operation and ready for a new re-connection with the grid.

b) Less time is spent by the operators to check and re-start the plant.

c) Limitation of the number of start and stop cycles for the geothermal pump.

d) Limitation of large precipitation of dirt along the vertical well (about 800 meters) interconnecting the geothermal water pump (installed at -800 meter) with the power block on the surface. Sometimes this large deposit can inhibit the start-up of the geothermal pump. Long and expensive maintenance operations would be otherwise required to dismount the downhole geothermal fluid pump and to clean the line.

e) Avoid the interruption of the flow in the pipeline and filter where the geothermal water is present. In fact when the plant is shutdown, it increases the risk to have scaling and precipitations inside the tubes and filters. Cleaning operation would require time and cost with negative effect on the availability.

f) Increased availability of the delivery of the heat to the district heating.

5. TECHNICAL ECONOMIC ANALYSIS

As already explained, in a geothermal plant in Germany the value granted for the electricity fed into the grid can reach up to 25 €c/kWh. The feed in tariff is granted for a period of 20 years. Due to the high costs for the deep drillings required (typically 4 – 5 km in the Molasse basin) the acceptable pay-back time of the overall project is often in the range of up to 10 years.

As a result any action that can increase the annual energy generation has a huge effect on the overall business plan and is valued correspondingly by customers.

For example for a typical 5 MWel plant, as shown before, roughly 500 kWel more can be achieved compared to a saturated single level cycle with same heat exchanger area. Assuming 8000 operating hours per year, the economic value of the additional power / energy produced would be 500 kW x 8000 h/year x 0,25 €/kWh = 1.0 M €/year (i.e 10.M € in 10 years) .

As explained in chapter 4, several redundancy and devices to increase the availability of the system have been implemented.

All these parts have been justified economically since an investment in increased redundancy that allows for example an increase of 1% of availability has an economic value of 1% x 8760 h/year x 5 MW x 0,25 €c/kWh = 109.500 €/year (1.1 M € in 10 years).

Furthermore, as anticipated in chapter 3, the economic impact of the additional energy production in case of heat decoupling shown in the previous chapter amounts to some 650 MWh/year x 250 €/MWh = 162.500 €/year (1.6 M € in 10 years).

The simple examples reported above show the utmost importance that both high nominal power and high availability have on the German market.

In such challenging frame conditions the features described in the previous chapters allowing high performance, availability and flexibility in regard of the decoupling of district heat are of primary importance. Together with the consistent track record of high performance and availability of Turboden ORC units on the German market they were instrumental for reaching the present success of Turboden in the German Geothermal market..

6. CONCLUSIONS: OPERATION STATUS

At the time of the paper conclusion (Dec. 2014), the three geothermal plants described are in operation since several thousands of hours, with performances higher than the guaranteed, and availability as per the following statistics.

Please note that the *recorded* time has been officially communicated by the operators to indicate the availability of the ORC plant in a *limited observation period*; however, the effective operation time has been longer as per Turboden's reports, as the plants have been started-up between December '12, and January '13.

Sauerlach: *Observation* Period: 13 months; Total *recorded* operation time: 8.648 hrs @ 95% availability

Duerrnhaar: *Observation* Period: 11 months; Total *recorded* operation time: 7.440 hrs @ 95% availability

Kirchstockach: *Observation* Period: 14 months; Total *recorded* operation time: 10.670 hrs @ 92,5% availability

Despite there have been major problems in the geothermal submersible pumps (not included in Turboden's scope of supply) that reduced the total energy potentially producible, the three plants have been successfully commissioned and fine-tuned, and formally accepted by the operators.

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