# Turboden, a Presentation of Recent Worldwide Developments and the Latest Technical Solutions for Large-Scale Geothermal ORC Power-Plants

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***Keywords***
*ORC, geothermal, binary plant, double pressure, hybrid cooling system*

## ABSTRACT

After our successful experience with three 5 MW geothermal power plants in Bavaria, and an upcoming 4th plant, Turboden has been enlarging its plants to up to 25MW electric power. A 25MW Turboden plant has been recently designed for the Aydin reservoir in Turkey. This paper focus on the technology of this plant, particularly describing the type of thermodynamic cycle, and the optimization drivers. The importance of configuration selected for optimized efficiency, and the design of key components like turbine and heat exchangers has been highlighted.

## 1. Geothermal Energy and ORC Technology

Geothermal energy is a renewable energy source, inexhaustible in the long term, available as base load power 24 hours a day, 365 days a year, in the form of hot water and steam from depths between 1 and 6 km. For temperatures higher than 100 °C it is technically possible and economically convenient to exploit this resource for the production of electrical energy. Further uses of waste heat are possible, for district/industrial heating or greenhouses. Even the byproducts of this process, such as carbon dioxide separated from the vapor phase, may be used in the food industry.

Geothermal fluids are brought to the surface using techniques similar to oil production, by means of wells that intercept deep, high permeability aquifers. These fluids exchange their heat (or pressure in the direct use with geothermal steam turbine) to thermo-electric (using the Rankine principle) conversion plants.

Although it accounts for less than 1% of today's world electricity production, geothermal is the renewable energy source with the greatest potential on Earth. The exploitation of this resource, which is extensively available, particularly at low and medium temperatures (up to approximately 180 °C / 356 °F), is therefore a promising frontier in terms of clean energy and responsible innovation.

The Rankine cycles with organic working fluid (ORC) have been used for several decades for power production, and are the only efficient way to produce electricity from geothermal sources with low or medium enthalpy.

The geothermal fluid, cooled by the ORC power-plant, is re-injected at depth by means of reinjection wells, thus creating a closed circuit where hot rocks constitute the primary heat exchanger.

## 2. Advantages of ORC Plants in Geothermal Applications

Binary power plants are the best technical and economical choice, for a wide range of resources and boundary conditions.

They have a definite thermodynamic advantage, in terms of power production, compared to the conventional flashed steam cycles, for resources at moderate temperatures (up to 150-180 °C) and can be used for electricity generation with low-temperature resources (close to 90-100 °C), which would not be feasible with flash steam.

For ORC systems, the turbine has no contact with the aggressive geothermal fluid, which is confined inside the tubes of the heat exchangers (a wide spectrum of materials can be employed case by case).

They are environmentally more acceptable than any other kind of geothermal power plant because the geothermal fluid can be segregated throughout the whole process. In this way the release of gases or other substances to the environment can be prevented, thus virtually eliminating pollution problems.

A wide selection of working fluids can be employed in order to optimize the thermodynamics of the ORC with variable geothermal heat resources.

Air cooled condensers can be employed as a further reduction of visual impact and water usage, over water cooling options.

Finally, ORC reduces the problems associated with scaling fluids: carbonate scale can be prevented by installing down-well pumps or by means of dosing systems, while silica scale is minimized by avoiding concentration of geothermal fluids caused by flashing and controlling the reinjection temperature.

## 3. Turboden Experience

After the construction of the first plants in Italy and Africa in the early Nineties, Turboden completed a 1,000 kWe plant in Austria. Turboden has also recently built a 1,500 kWe plant in Soultz-sous-Forets (France)), the first EGS (Engineered Geothermal System) plant in Europe. The water, injected under pressure, reaches deep impermeable rocks fractured by the drilling where it is heated at 180°. In Q4 2012 Turboden started up the first supercritical ORC plant in Europe, a 500 kW prototype with hybrid direct cooling, and tested its flexibility with highly variable heat input. Turboden has made plant performance optimization a top priority and has thus won a tight competition achieving the award of tenders for the design, construction and start-up of 3 geothermal ORC plants in Bavaria (5+ MW each). These plants have been successfully commissioned and started-up in Q1 2013. Geothermal water at 140 °C is pumped from a depth of approximately 4000 metres. These plants are air-cooled and carefully integrated into the rural context and prepared to supply heat to the existing district heating network.

A further 5 MW geothermal plant is presently under commissioning in the Oita prefecture in Japan, Kyushu Island. This plant uses a geothermal source with about 15% steam quantity at 140 °C.

Finally, a 3 MW ORC plant has been awarded to Turboden and is presently under construction for the community of Afyonkarahisar (Turkey). It will exploit a 110 °C geothermal liquid source by means of an ORC which will be water cooled. This plant demonstrates that small-scale / low-temperature ORC plants are feasible, even in less subsidized markets.

## 4. Turboden Solutions for Turkish Frame Conditions

In a geothermal plant in Germany, like the ones supplied by Turboden[1], the value granted for the electricity fed into the grid can reach up to 250 EUR/MWh (with current exchange rate 275 USD/MWh).

In comparison, under Turkish frame conditions, the feed in tariff is substantially lower (between 105 and 118 USD/MWh depending on the share of local content). On the other hand drilling costs and drilling risks are substantially lower allowing good feasibility and relatively low resource development risks for investors. In addition production wells are typically self-flowing wells that can be operated without downhole pumps, hence eliminating the associated technical risk and electrical own consumption (this consumption can reach up to 20% of gross power in a typical German project). As a result the Turkish market has developed to be the biggest %-growth market in the world in the last 5 years for medium enthalpy geothermal plants (175 MWel installed in 2014, all of which based on ORC units).

A first result of the lower value of the electricity production is that the additional cost for the refrigerant R245fa (optimum solution for the thermodynamic cycle employed in Germany by Turboden) is normally not justified in terms of additional cash flow from electricity production. In addition flammability of working fluids is rarely a concern in Turkish geothermal power plants as the plants are typically realized in not inhabited areas. Turboden therefore mostly proposes plants based on hydrocarbon working fluids for Turkish projects.

Typical Turkish frame conditions provide for self-flowing wells with wellhead pressures that are well below gas breakout pressure. Therefore at wellhead a two phase geothermal fluid is available for electricity production. Normally the two phases are separated at wellhead and sent separately to the ORC unit. The typical solution considers using the two flows in parallel for working fluid evaporation; in particular as per Fig. 1 the solution considers employing a single evaporator shell, with two dedicated and separate tube bundles; one for the geothermal steam, one for the geothermal brine. The condensate from the vapor evaporator bundle is mixed with brine exiting the liquid evaporator bundle and used for working fluid preheating.

Due to the presence of incondensable gases the vapor flow has a characteristic heat release curve with heat capacity that decreases together with temperature reduction. The exact shape of the heat release curve depends on the actual characteristics of the stream (steam fraction, NCG fraction and pressure).

The fact that a part of the evaporation heat comes from the vapor condensation can help in matching the heat release curve with the heat absorption curve of the working fluid. In general the additional performance achievable by using a two pressure level (that was the optimum thermodynamic solution employed by Turboden in Germany) decreases with increasing steam content in wellhead flow. This is shown clearly in the temperature/heat diagrams below that represent a single pressure level cycle with isobutane as working fluid with a 140°C geothermal source. In the left figure 2 (case a) negligible steam content is assumed while in the right figure 2 (case b) a vapor flow of 6% of total mass flow is assumed (5% steam and 1% NCG at 4 Bar abs pressure).

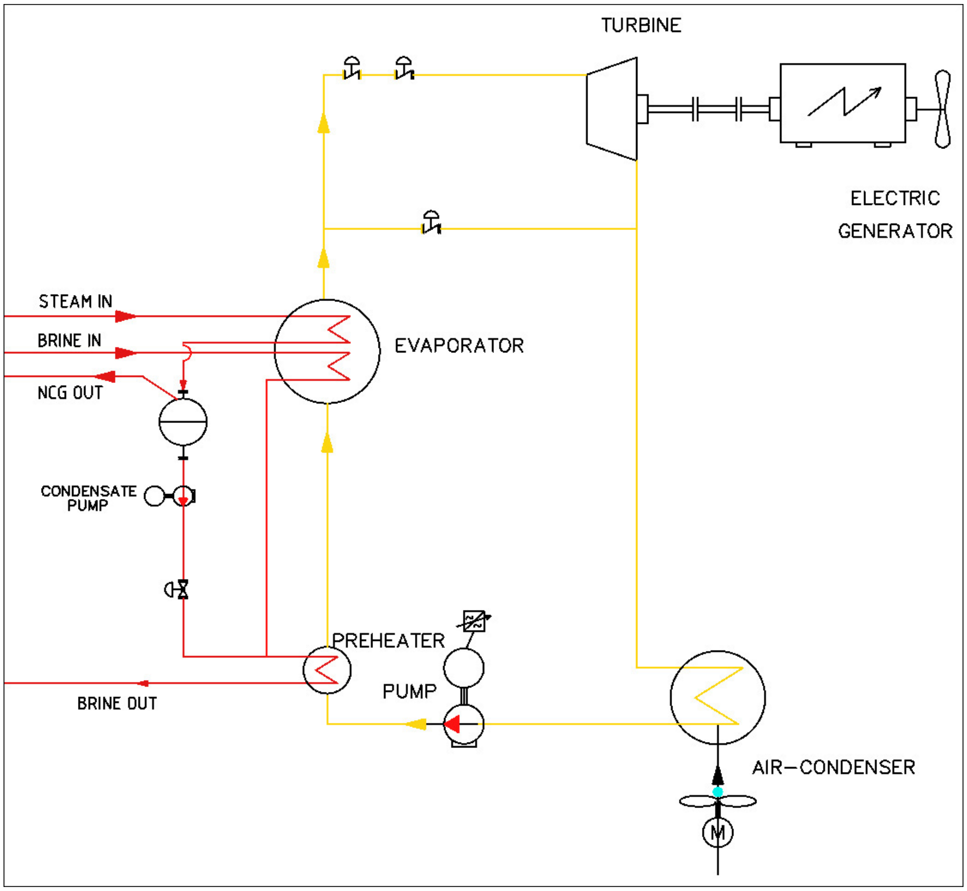


**Figure 1.** Conceptual P&I for pressure single level cycle using vapor and brine for working fluid evaporation.

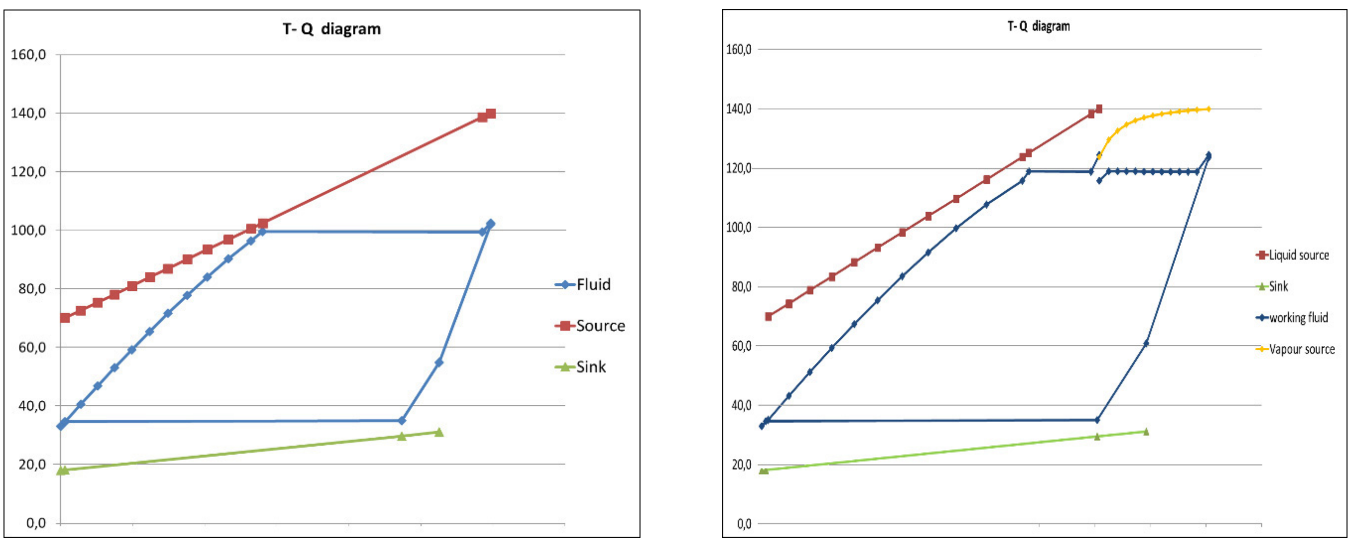


**Figure 2.** Temperature/Heat diagram of single pressure level isobutane cycles on a 140°C geothermal source without vapor content (case a: left side) and with 5% steam plus 1% NCG content (case b: right side).

The diagram on the right (case b) shows that the additional heat coming from the vapor condensation covers a relevant part of the evaporation heat of the working fluid and leads to a similar slope of brine cooling and working fluid preheating lines in the temperature/heat diagram. It is evident that the matching of working fluid preheating and brine cooling curves is not good in the left diagram (case a) while it is good in the right diagram (case b).

The additional net power that can be achieved with a two pressure level cycle with the same heat exchange surface and working fluid has been calculated for both scenarios. The calculations have been run with the following assumptions:

Geothermal Fluid temperature: 140°C

Vapor content: case a 0%; case b 6% (5%steam and 1% NCG at 4 Bara pressure)

Condensing temperature: 35°C

Minimum brine outlet temperature from ORC: 70°C

Turbine isentropic efficiency: 85%

Pump isentropic efficiency: 75%

The additional power of the 2 pressure level cycle is 6.5% for case a while it is negligible for case b.

The above considerations show that the two pressure level solution adopted in the successful German plants is advantageous only in some Turkish projects (with low steam content available) while in other cases (with high steam content available) a one pressure level cycle will be the best choice.

## 5. Larger Scale ORC Geothermal Plant Power Plant Components and Configuration Implemented in the 25 MW Project

After the consolidated presence in Turkey with 5 plants awarded, Turboden has recently signed a MoU for a 25 MW power-plant.

As described in the previous chapter, Turboden has compared different configurations and working fluids before selecting the most effective, both in terms of economic and technical point of view.

- Working fluid. The best working fluid in terms of reduction of irreversibility losses considering the heat release curve of the geothermal water and steam, is i-butane. This is also evident as the critical temperature is very close to the inlet temperature of the geothermal steam and brine.
- Configuration. The adopted configuration considers as the optimum solution, both in terms of producible energy, Capex, and simplicity of operation and maintenance, a single pressure level saturated cycle, with two turbines coupled to the same electrical generator. Each turbine receives the same quantity of butane flow-rate, evaporated by means of two evaporators in parallel with the geothermal steam and brine. The system is so conceived, that it is possible to feed at design point each heat exchanger with 50% of the total geothermal flow, so that in case of maintenance (e.g. cleaning) of one evaporator (or pre-heater), it is possible to feed the other side with its design flow, with no risk of solid deposits due to velocity inside the tubes lower than the design ones. Furthermore, it is possible to make maintenance to one of the two turbines, by simply de-coupling the turbine and keeping the other running and producing electricity.
- Turbine. At the heart of the plant two 12.5 MW Turboden axial turbines have been the key for the maximization of the power output all over the wide range of operation. In fact, thanks to the multistage axial configuration, not only reliability and ease of maintenance have been optimized (Turboden has a fleet of more than 250 ORC power plants in operation with proprietary axial multi stage turbines, with an average availability > 98%), but also the net energy producible all over the year is expected to be the highest among all the other solutions offered by the market. This has been possible thanks to an isentropic efficiency always > 85% all over the range of operation.
- 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 geothermal steam and brine. To avoid corrosion issues and increase durability of the heat exchangers, the material adopted for the parts in contact with geothermal steam, is a suitable duplex steel (e.g. tubesheet, distributor channel, partition plate and heat exchanger tubes). On the ORC working fluid side traditional carbon steel is used for the heat exchangers shells and for most of the piping. The system is 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.
- 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 (always above ambient pressure) and own consumptions. In order to avoid leakage of working fluid, 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. Tube bundles are made in carbon steel, the heat exchanging tubes are finned tubes; material of the fin is aluminum. The air condenser is composed by a large number of bundles interconnected each other in parallel mode. Two passes fluid side has been considered, in order to avoid the typical sub-cooling undesired effect traditionally present in the standard one-pass solution so far implemented in similar plants by other suppliers.

- ORC feed pumps. The configuration able to guarantee the highest availability has redundant pumps (3x50%) for each turbine. In case of failure of the one pumps or other devices and auxiliary connected to it, the control system is programmed to automatically switch on the stand-by redundant pump without shutdown of the ORC plant.
- Hybrid cooling system. This solution envisages the use of an Air Cooled Condenser, with the optional addition of a water cooled condenser and a Cooling Tower to be used in the summer season to increase the Power Output. These components can be easily added in a second stage, with maximum 1 day stop of operation of the plant, thanks to blind flanges already present on the exhaust ducts of the turbines. This feature will increase the net power output all over the range of operation, obviously showing the highest benefit during the hot dry season.

## References

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