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Binary power plants
for the high enthalpy well-head generation

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Binary plant, ORC, wellhead, efficiency comparison, geothermal plant, high enthalpy

ABSTRACT

Binary Technology is globally recognized as a mature technology for power generation from various heat sources. Geothermal is one of the renewable sources of energy most suitable for binary application. The use of a binary fluid allows the generation of electricity from very low temperature liquid dominated geothermal sources, to high enthalpy steam dominated resources.

While traditional flash steam power plants exploit only the steam fraction of the geothermal flows, the binary ones can use also the liquid part, in order to increase the specific utilization of the resource. Additional positive feature is that 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).

Furthermore, ORC plants 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. In particular, the possibility to make full reinjection of geothermal fluids is a relevant feature for the long term exploitation of a pressurized reservoir.

The paper will provide information about the advantages of using binary technology for well-head power generation, as compared to the traditional flash steam turbines.

While the use of a binary fluid allows generation of electricity from very low temperature liquid dominated geothermal sources, binary has become cost effective also in high enthalpy steam dominated resources.

Traditionally ORC technology has shown 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 has been shown to be applicable for electricity generation with low-temperature resources (close to 90-100 °C).

In recent international bids, binary technology has been proven competitive in terms of performance and cost when applied to high enthalpy steam sources with plant size of 5 – 15 MWe per module.

1. Introduction: ORC technology and binary geothermal plants

Turboden S.p.A. is an Italian company founded in 1980 by Prof. Mario Gaia of Politecnico di Milano. Today it is world leader in designing, manufacturing and supplying ORC systems, with more than 360 references worldwide. Since 2014, Turboden is part of the Japanese industrial giant Mitsubishi Heavy Industries, world leader for installed power from geothermal sources.

Binary power plants are systems that utilize a secondary working fluid (organic fluid), with a low boiling point and high vapor pressure at low temperatures as compared to steam.

While traditionally binary power plants have been utilized for low temperature resources (close to 90-100 °C), where the source could not be exploited with flash steam, and for resources at moderate temperatures (up to 150-180 °C), where the binary cycle has demonstrated thermodynamic advantages, in terms of power production, compared to the conventional flash steam cycles, binary power plants have been further able to stretch its applicability becoming the best technical and economical choice, for a wider range of resources / boundary conditions.

In particular the utilization of a modular approach where the plant grows together with the geothermal exploration activities is recently receiving a lot of attention in the geothermal community. The modular approach allows to significantly reduce the required equity for project development due to the fact that electricity generation is possible very quickly after the first wells are in operation therefore allowing to partially finance the expansion of the facility with the cash flows generated by the first modular plants deployed. Typically, the size of a modular plant is between 5 and 15 MWe. ORC units are particularly well suited for this task because high efficiency of the cycle components can be achieved also for plants in this size range.

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

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

If a cooling tower is selected as cooling system, as in the traditional flash steam cycles, the steam condensate (if enough) can be utilized as make up water.

As an alternative, air cooled condensers can be employed as a further reduction of visual impact and water / resource usage. In this way there is no steam loss to the atmosphere (through the cooling tower), therefore total reinjection of geothermal fluid is achievable.

Finally, ORC power plants reduce the problems associated with scaling fluids: carbonate scale can be prevented by selecting a higher separation pressure (or by installing down-well pumps) or by means of dosing systems. Silica scale is also minimized by avoiding concentrating the geothermal fluid caused by flashing and controlling the reinjection temperature.

2. Performance comparison between different Geothermal Power Plants

Relevant literature comparing the efficiency of different plant configurations exist mainly for plant capacity larger than 50 MWe per unit. Typically, a superiority of flash cycles or a combination of binary and flash plants has been derived in the past at these plant sizes starting from an enthalpy of 1,000 kJ/kg [1].

Due to the fast growing learning curve, both in terms of plant efficiency and in terms of cost optimization, ORC units are more and more competitive under frame conditions that have traditionally been considered only viable for flash or combined cycle technologies. Another driver for the implementation of ORC units is the growing interest for modular or wellhead plants.

A wellhead plant is made of modular equipment located on the same well pad where the production of geothermal fluid is carried out. A wellhead plant requires simple equipment in the resource gathering system, and the power is limited to the capacity exploitable from that specific well (or more wells, if the well pad has more than one production well). Typically the separation pressure is optimized on the pressure level of the most powerful well. More than one well head plant can be put on the same well pad, thus increasing the local capacity generated: by means of multiple generators the power produced on a single well pad can reach 30 MW (e.g. with 3 high enthalpy wells and three generators of 10 MW each).

With the rapid expansion of the industry in Eastern Africa for the last decade the demand for wellhead power plants has increased. The modularity and simplicity of a wellhead power plant allows for accelerated construction time and shorter time period from drilling completion to power production.

In this paper the performances of different wellhead power plant technologies will be compared for a plant capacity of about 8 MWe per unit. A single flash, a binary plant and a hybrid solution (single flash plant coupled with a binary plant utilizing the brine) have been chosen for this comparison. This is consistent with the solutions proposed by the market as the solution of double flash cycles is typically not cost effective at these plant sizes regardless of the technical feasibility.

Diagrams representing the power plants configurations are shown in the Figures 1, 2 and 3.

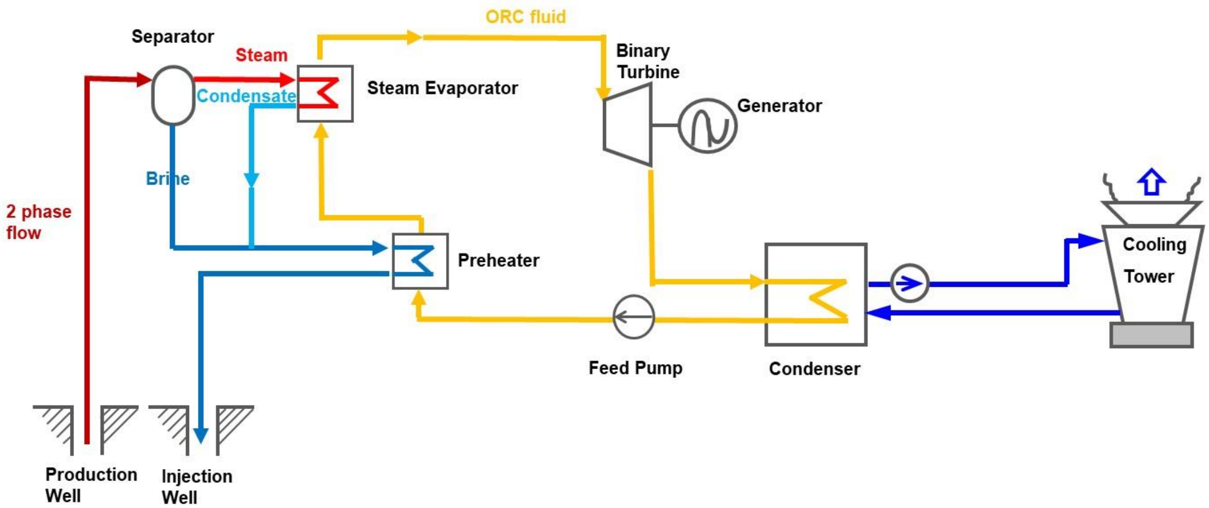

Figure 1: ORC power plant

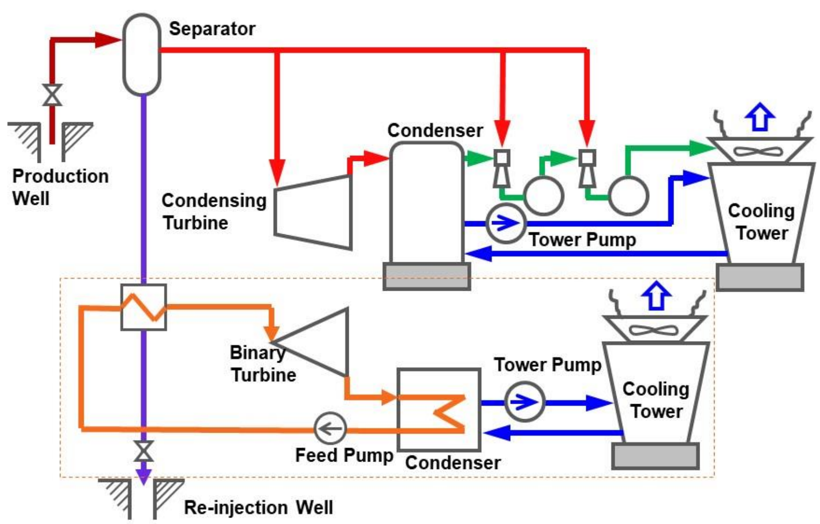

Figure 2: Hybrid power plant (Single Flash + ORC)

As shown by figure 1, the ORC power plant exploits the geothermal steam to vaporize the organic fluid; then the steam condensate is collected and mixed with the liquid brine for the preheating of the organic fluid. Differently, in the Hybrid configuration (Fig. 3) the ORC exploits only the separated brine before the reinjection.

The Single Flash plant is made of a condensing steam turbine, expanding in a condenser cooled by an open loop of cooling water with forced cooling tower. One of the reasons why single flash plants make depletion of the reservoirs is the fact that the geothermal condensate is used as make up water of the cooling tower, therefore almost all of the separated geothermal steam goes into the atmosphere.

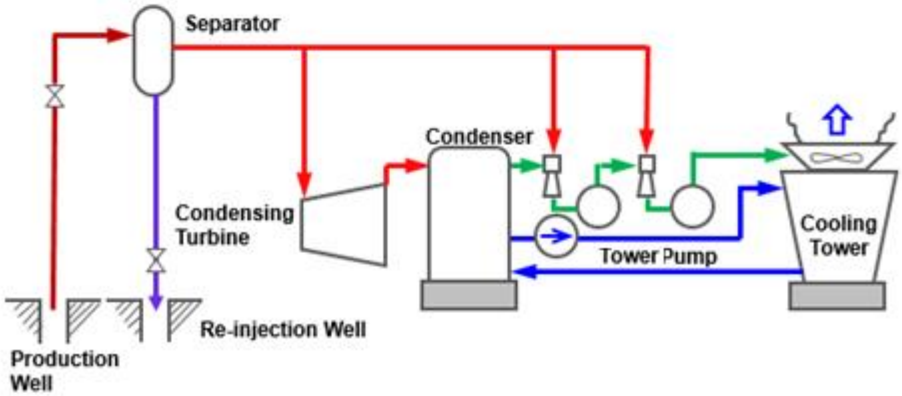

Figure 3: Single Flash power plant

2.1 Hypothesis, assumptions and results

The following main data have been considered for the evaluation (as reported in Table 1):

Variable	**Unit of measure**	**Case 1**	**Case 2**	**Case 3**
Specific Enthalpy	kJ/kg	1526	1717	1373
Saturated Liquid Temperature	°C	330	355	305
NCG content in the geofluid	%w/w	0.6	0.6	0.6
Silica content	mg/kg	215	215	215
Dry Bulb Temperature	°C	23	23	23
Wet Bulb Temperature	°C	17	17	17
Relative Humidity	%	55	55	55
Cooling Water Temperature	°C	21	21	21
Atmospheric Pressure	bar(a)	0.800	0.800	0.800

Table 1: Main Data input

Moreover the following geofluid productivity curve (see Fig. 4) has been arbitrarily chosen in order to allow an optimization of the separation pressure for the different plant technologies for the purpose of fair comparison.

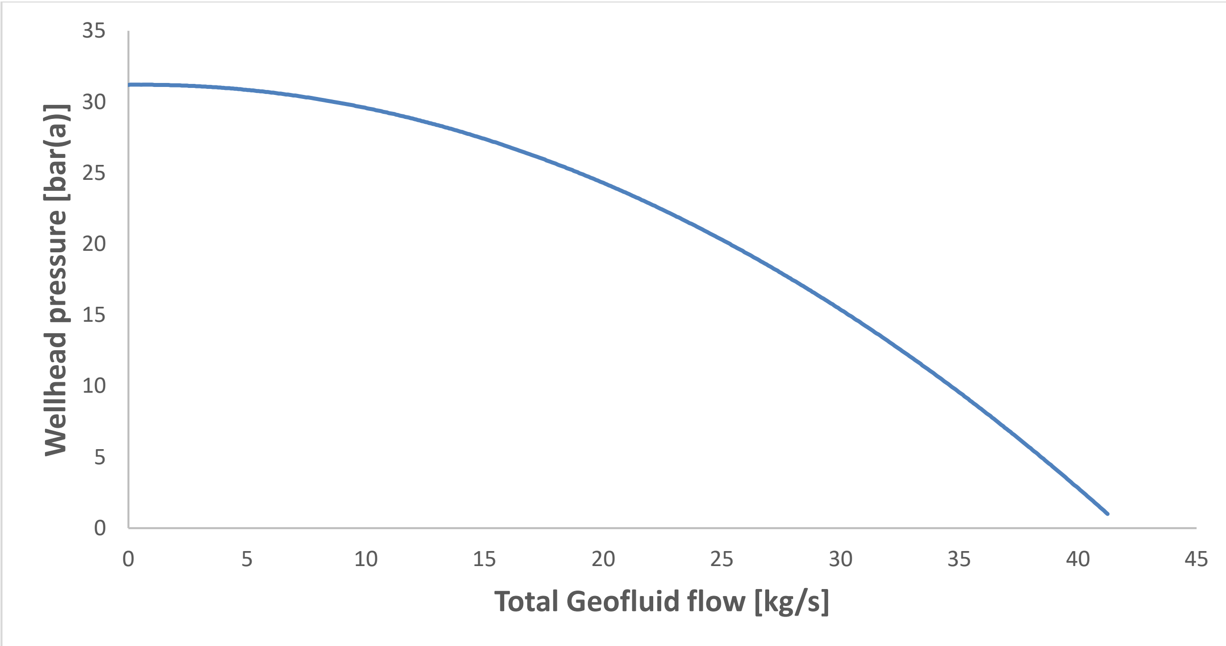

Figure 4: Well Deliverability/Production Curve used for technology comparison

For simplicity the same productivity curve has been considered for each reservoir temperature case.

On the productivity curve, for a given enthalpy the wellhead pressure affects not only the total geofluid available, but also the vapor fraction: the lower the wellhead pressure the higher the vapor fraction. As most of the silica goes with the separated liquid, having lower pressures and higher vapor fractions lead to higher silica concentration on the brine fraction; in this paper it has been considered to cool down the brine to a point where the silica saturation index is one (SSI = 1).

The ORC main consumption is made by the organic fluid pump. However, for high enthalpy systems, the organic fluid works at relatively low pressures, and the consumption of the pump is lower than 5% of the gross power.

For all of the plant configurations, cooling system electric consumption is calculated as 1.5% of the thermal power for each configuration. This is valid for most of the wet cooling systems, including the consumption of fans and of the cooling water pumps.

Steam ejector motive fluid consumption, required by the condensing steam turbine in the flash system and hybrid system (see Fig. 3 and 4), is calculated based on required suction mass flow and available motive steam pressure [6].

The results for the three different configurations are reported below in Tables 2, 3 and 4. The performances have been simulated with state of the art data and programs (Turboden proprietary models, ASPEN) considering typical component efficiencies for this plant capacity.

Binary Power Plant

Variable	Unit of measure	Case 1	Case 2	Case 3
Separation Pressure	bar(a)	8.0	8.5	7.0
Hot Inlet Temperature	°C	170.3	172.9	164.8
Hot Outlet Temperature (SSI =1)	°C	103.5	124.1	92.5
Cold Inlet Temperature	°C	21.0	21.0	21.0
Cold Outlet Temperature	°C	31.0	31.0	31.0
Net Efficiency	%	16.9%	17.4%	16.4%
Net Power	kW	7,715	9,297	6,525

Table 2: Results for the ORC Binary Plant

Hybrid Power Plant

Variable	Unit of measure	Case 1	Case 2	Case 3
Separation Pressure	bar(a)	8.5	9.0	8.5
Hot Inlet Temperature	°C	172.8	175.3	172.8
Hot Outlet Temperature	°C	102.9	123.5	90.9
Cold Inlet Temperature	°C	21,0	21,0	21.0
Cold Outlet Temperature	°C	31.0	31.0	31.0
Net Efficiency	%	14.4%	15.5%	13.8%
Binary Net Power	kW	896	564	1,158
Condenser Pressure	bar(a)	0.150	0.150	0.150
Steam Turbo-Generator efficiency	%	80%	80%	80%
Steam Turbine Net Power	kW	7,104	9,112	5,566
Total Net Power	kW	8,000	9,676	6,724

Table 3: Results for the Hybrid Power Plant

Single Flash Power Plant

Variable	Unit of measure	Case 1	Case 2	Case 3
Separation Pressure	bar(a)	7.5	8.0	6.5
Hot Inlet Temperature	°C	167.7	170.4	161.8
Cold Inlet Temperature	°C	21.0	21.0	21.0
Cold Outlet Temperature	°C	31.0	31.0	31.0
Condenser Pressure	bar(a)	0.150	0.150	0.150
Steam Turbo-Generator efficiency	%	80%	80%	80%
Net Power	kW	7,130	9,141	5,661

Table 4: Results for the Single Flash Power Plant

A graphic representation of the results is shown in the following figure:

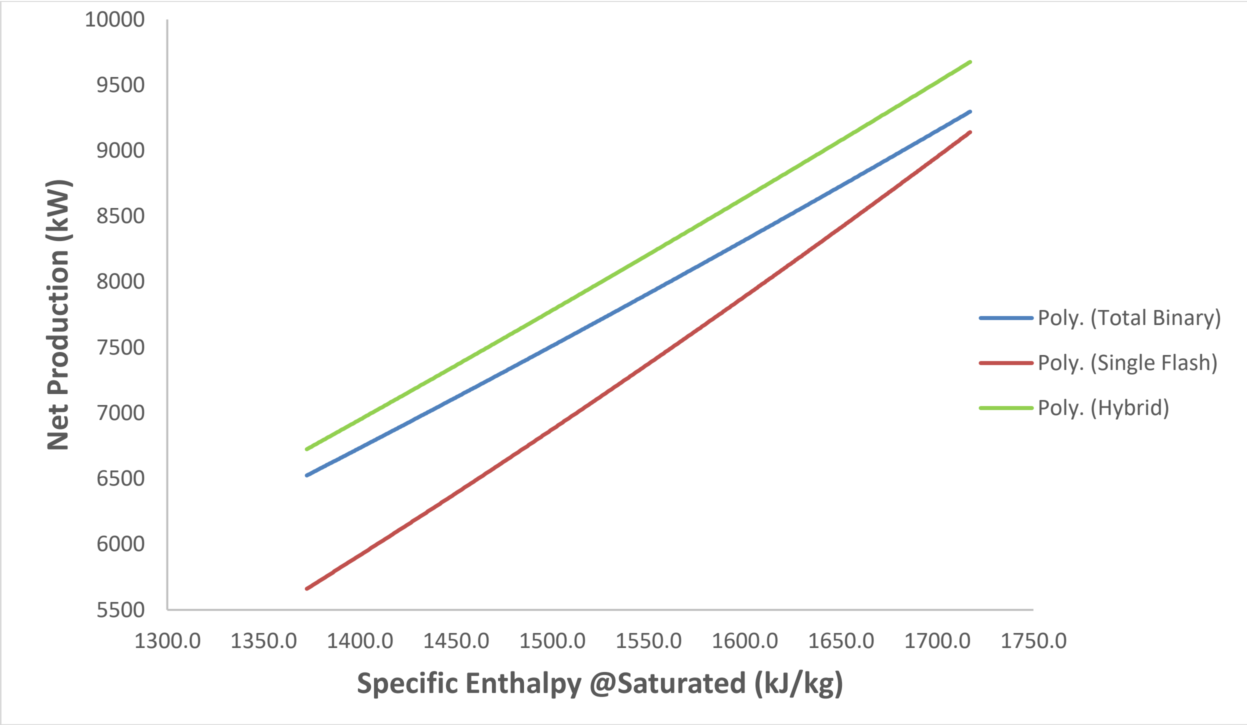

Figure 5: Net electricity production for the three configurations considered

The results show that with the assumptions of this study, an ORC power plant has higher performance than a single flash plant for source enthalpies up to 1700 kJ/kg. Remarkably, this result is obtained assuming a relatively low NCG content in the brine. With higher NCG content in the brine the advantage of using ORC cycles would be even more evident, due to the higher consumption of the steam ejectors, required by condensing steam turbine.

A hybrid solution is capable of exceeding the performances of the binary ORC unit, however it has to be noted that due to the small capacity of the bottoming ORC plants (in the range of 0,5 – 1 MWe), the specific capex of this solution is utterly high. In practice, adding an ORC unit on the spent brine of a flash system is more economical, if a single ORC plant is coupled to the unused brine of several wells. However, in such case the simplicity of the modular approach is partially lost because of the necessity to collect the brine from multiple wells.

In any case, the possibility to repower an existing single flash system by adding an ORC unit on the separated hot brine, can be attractive if it is possible to cool down the brine at ORC outlet to a temperature where the Silica Saturation Index is greater than 1, and the logistics of the brine collection from multiple wells is manageable both technically and economically.

2.2 Cost comparison

Considering the significant variability in the costs of different projects depending on specific site conditions, different scope of supply, different economic dynamics, and no analytic analysis of the costs of the different technical solutions is attempted in this paper.

However recent experience in competitive tenders, shows that capex of binary systems is typically lower than that of steam or hybrid solutions.

As an example, the results from a recent public tender are reported below (the results are the average of 4 different bidders):

	Performance	**CAPEX (for plants of size 10 MW and smaller)**
Water-cooled Binary (reference)	Reference case	Reference case
Single Flash	-8%	+11%
Combined (Single Flash + Binary)	+1%	+11%

Table 4: Results for the Single Flash Power Plant

3 Conclusions

As shown in this study, binary ORC technology present both quantitative and qualitative advantages even for high enthalpy resources (up to 1700 kJ/kg).

This is more evident for modular units with capacity compatible with the very popular wellhead approach (smaller than 10 MW).

We have numerically demonstrated that ORC technology is capable to exploit both the separated hot brine & steam (two phase flow), with higher performance and lower Capex than the single flash solution. The results are confirmed by the recent results in public tenders where the ORC technology has been selected for wellhead projects in Africa.

Hybrid systems with an ORC unit added on the separated brine from a single flash cycle are capable of exceeding the performance of binary units. However, the addition of an ORC is typically not cost effective at the sizes typical for modular wellhead plants. On the other hand, if it is technically and economically feasible to collect the unused brine from multiple wells, the addition of an ORC unit to existing flash plants can make technical and economic sense.

The authors are confident that in the near future, the wellhead ORC plants will take a larger share of capacity for generation from remote or existing geothermal sources.

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