Recent trends in research and application of ORC plants for geothermal energy use

Alessandro Franco, Maurizio Vaccaro

Department of Energy, Systems, Territory and Constructions Engineering (DESTEC)
University of Pisa, Largo Lucio Lazzarino, 56126 PISA (ITALY)

email address: alessandro.franco@ing.unipi.it

Keywords: Geothermal; Organic Rankine Cycle (ORC) Binary Power Plants, Optimum design

ABSTRACT

The aim of this paper is to analyze the status of the development of ORC in connection with geothermal energy use, focusing on the solutions that have been applied in the ORC geothermal industry and that have been proposed in the scientific literature mainly in the last ten years. The paper analyzes also the further research perspectives that still need efforts in the research community. Some case studies are here analyzed, with reference to the objective of this paper. An outline is the review of some significant key-point, and the analysis of the future perspective both in industrial implementation and research advances.

In particular the authors would analyze how the various solutions have been implemented and the problems encountered. The task is also to discuss the matching between technology transfer and industrial development and the future perspectives of ORC plants for geothermal energy conversion in liberalized market conditions without considering financial incentives.

1. INTRODUCTION

The first experience of obtaining electric power based on geothermal heat use was gained at the Paratunsky geothermal reservoir (Kamchatka) at Russia in 1967. Geothermal binary two-circuit pilot power plant with capacity of about 500 kW was created here for the first time in the world (Povarov et al., 2003). Today, after about 50 years of history and development it is possible to trace a first standpoint about the development of binary cycle power plants technology, today better identified as ORC (Organic Rankine Cycle) plants technology.

ORC plants have been identified since the beginning of the 90s as the basic reference technology for increasing the use of medium to low temperature geothermal resources for electricity production purposes. As it has been largely addressed in the scientific literature about geothermal energy in the last twenty years, the medium to low temperature reservoirs with pressurized water, in the temperature range between 70 °C and 150 °C, are the most diffused all around the world (Steffansonn, 2005).

The potential use of geothermal resources has been a remarkable driver for market players and industry operating in the field of geothermal energy conversion. For this reason medium to low temperature geothermal resources have been the object of recent rise in consideration, with strong reference to the perspectives of development of ORC technology. This has been driven by the growth of the geothermal market around the world due to subsidies to ORC applications by the national and local Institutions, mainly in the European Union, together with the development of the geothermal industrial branch in emerging countries of Central America, Africa and Asia.

In the recent years a significant attention to the ORC development and utilization has been addressed by the scientific community and academic researchers and by the factories involved in geothermal energy market. Both theoretical and practical solutions based on the optimum matching among geothermal resource characteristics, ORC working fluid, and thermodynamic cycle have been largely proposed in the last 15 years. Notwithstanding the diffused debate, the industrial applications of ORC plants in geothermal energy field seem to be limited only to some specific technologies, and in specific cases the economic results after some years of exercise are not always positive or at least the technology transfer has to be analysed.

The objective of the present paper is to define a kind of balance about the recent diffusion of ORC power plants and the perspectives of future development of ORC power plants for geothermal reservoir exploitation, analyzing the different perspectives coming from industrial and academic research and commercial development defining the perspective of development of a geothermal power ORC industry, mainly in connection with modular small power solutions (often in the range between 200 kW and 10 MW) that can operate with good efficiency in a quite large range of variation of the characteristics of geothermal source, that is in general the key point for the development of renewable energies, as clearly evidenced by the recent development of PV power, wind power and mini-hydro energy.

2. ORC POWER PLANTS: STATE OF THE ART

Binary technology allows the use of medium to low temperature water dominant reservoirs and makes geothermal power production feasible even for countries lacking high enthalpy resources at shallow depth. Moreover the perspective of using geothermal resources at temperatures below 150 °C made available interesting resources at quite reduced deep in zone characterized by high enthalpy geothermal fields, Fig. 1. The availability of the resource at a quite low deep (e.g. 1000-1500 m below the ground level instead of 3000-4000 m) permits interesting reduction of the costs connected to the drilling phase and the geological risk.

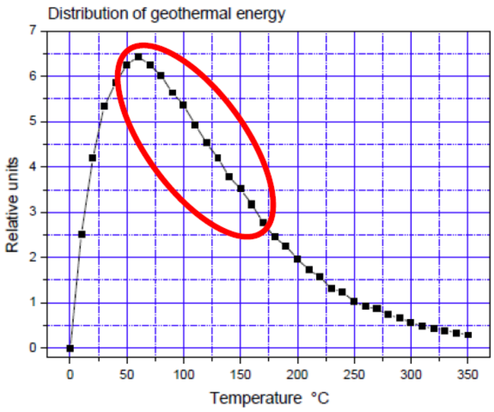


Figure 1: Geothermal resources distribution worldwide, estimated (Stefansson 2005).

As clearly evidenced in Fig. 2, the plant comprises two separate sections: the geothermal fluid loop and the power cycle. Geothermal fluid loop and power cycle are completely separated. The connection point is represented by recovery heat exchanger (RHE). In this way "Nearly zero emission" plants (mainly for all-liquid geofluid) can be conceived. Moreover this kind of plant is suitable for integration with other energy sources (solar, biomass, energy recovery from waste, etc.).

Concerning the geothermal fluid loop, for the gathering of the geothermal fluid a layout with a doublet (1 production well and 1 reinjection well) is the typical solution, even if solutions with multi well configurations are considered, mainly in connection with plants of increased size (or with modularization of the installations).

For binary plants two different systems currently are state of the art, the Organic Rankine Cycle (ORC), mainly based on the use of hydrocarbons or refrigerant, and advanced cycle based on supercritical cycle and the Kalina Cycle. Kalina cycle raises considerable interest as it makes it possible to produce electricity from cooler geothermal sources (typically within the 100-120°C temperature range, exceptionally down to 70-75 °C depending upon the availability of a cold water source for re-condensation of working fluid).

The binary power plants have a small environmental impact due to the "confinement" of the geofluid. In a binary cycle power plant the heat of the geothermal water is transferred to a secondary working fluid, usually an organic fluid that has a low boiling point and high vapor pressure when compared to water at a given temperature. The cooled geothermal water is then returned to the ground by the re-injection well to recharge the reservoir (DiPippo, 2008).

Of the about 12,600 MW of geothermal plants installed worldwide, about 1800 MW, namely 280 power plants corresponding to 12.5%, use ORC or steam/ORC combined cycles (Bertani, 2015). The diffusion of such kind of plants is increased in a meaningful way in the last ten years, as clearly discussed in the next section. It is possible to estimate that a total amount of about 1050 MW has been installed in the last ten years, mainly under the impulse of some manufacturers.

The geothermal binary plants currently in operation can be divided according to different classifications: the first and more meaningful is surely the dichotomy between "stand-alone" or "bottoming cycles" but another difference is related to the power output.

Binary plants can be classified according to the cooling system used: plants with a wet cooling system, where the working fluid is condensed by cooling water, and plants with a dry cooling system, where the heat is rejected directly to the air. Relevant differences can be evidenced in the operating fluid and in the main thermodynamic variables.

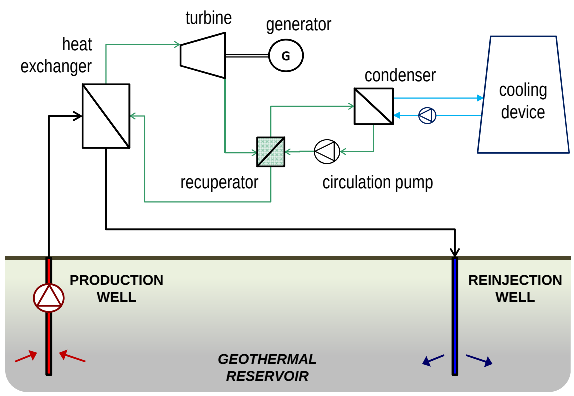


Figure 2. Binary cycle power plant schematic view

2.1 Binary cycle power plants: main thermodynamic elements

The binary plants utilize a secondary working fluid, usually an organic fluid (typically a hydrocarbon or a refrigerant fluid), that has a low boiling point and high vapour pressure at low temperatures when compared to water. The secondary fluid is operated through a conventional Rankine cycle o through a Rankine cycle with superheater. This cycle is also called the organic

Rankine cycle (ORC). In a binary cycle typically, geothermal water is then reinjected in order to recharge the reservoir and complete the renewable energy utilization cycle. For this reason the geothermal plant has no emissions to the atmosphere except for water vapor from the cooling towers and a miniscule loss of working fluid during the operation cycles. In a binary geothermal plant where there is not a sufficient supply of water for an evaporative cooling system, heat must be rejected to atmospheric air. This heat rejection is accomplished through the use of large air-cooled condenser units in which air is forced through several rows of long individually finned tubes by large fans. The operational experience has confirmed the advantages of binary and steam/binary combined cycle power plants, not only for moderate enthalpy water dominated resources with chemically aggressive brines, but also for high enthalpy geothermal fluids, with high non-condensible gas content. There are many different technical variations of binary plants; the most common are Organic Rankine Cycles (ORC).

ORC plants are relatively poor converters of heat into work. First Law efficiency typically lies in the range of 6–10% even if the plants can operate with very high Second Law or exergetic efficiencies (between 30 and 45%) because the motive forces are low-temperature and low exergy sources.

The remaining amount is divided among the exergy of brine reinjection (15-20%), turbine and pump pressure losses (10-15%), heat exchanger (10-15%) and condenser losses (15-25%). Binary plants vary in size from hundreds of kilowatts to about 100 MW.

The small development linked to modular construction is mainly due to the large variety of temperature, pressure and chemical composition of the geothermal brine (this last value define a boundary on the value of reinjection temperature) that make difficult the definition of solutions using “standard machinery”.

Various authors like DiPippo, Kanoglu, Gnutek, et al., Kose and Franco and Villani (2009) have proposed methods for raising the efficiency of ORC plants, by using a cascade of evaporators with both a high and low-pressure turbines, or by using two cycles operating with fluids of different thermodynamic characteristics. But these methods significantly increase the investment expense, as the number of main items, and plant complexity increases.

Binary ORC power plants exploiting low-temperature geothermal heat sources have been studied considering different perspectives: for example through design analysis (Franco, 2011) and through design optimization (Madhawa Hettiarachchi et al., 2007; Astolfi et al., 2014; Wang et al., 2014).

The use of different thermodynamic cycles has been largely investigated: the cycle of specific interest are: the subcritical (Rankine and Rankine with superheater), supercritical and transcritical thermodynamic cycles and the Kalina cycle (Chagnon-Lessard et al., 2016).

A comparison of using different working fluids has been performed by several researchers Hung (2001), Drescher and Brüggemann (2007) and Franco and Villani (2009). The impact of turbine efficiency on ORC net power output calculations was investigated too, by Pan and Wang (2013).

Plant optimization embraces three fields: plant layout including selection of the opportune working fluid, adjustment of process parameters and dimensioning of equipment and machines. For performance analysis of geothermal power plants, first and second law efficiencies are usually considered. First Law efficiency is defined with respect to the specific enthalpy of geothermal source. It does not reflect the thermodynamic quality of the conversion process since the same efficiency can be obtained for widely different thermal potentials. The temperatures of geothermal fluids are relatively low, so the First Law efficiencies of geothermal power plants are also inherently low. Consequently, the difference between the First Law efficiency of a good performing and that of a poorly performing geothermal power plant located at similar sites is small. It then becomes difficult to make a comparison on the basis of First Law efficiencies only. Second law efficiencies are more suitable to assess their performance, but first law efficiency is an important indicator to understand the heat that has to be discharged to the environment. Two kind of different definition are available

$$\eta_I = \frac{W_{net}}{m_{geo}(h_{in})_{geo}} \tag{1}$$

$$\eta_{II} = \frac{W_{net}}{\dot{m}_{geo}[(h_{in} - h_0) - T_0 \cdot (s_{in} - s_0)]_{geo}} \tag{2}$$

where h_0 and s_0 are the reference value for enthalpy and entropy. Otherwise a different definition of First and Second Law efficiency can be the following:

$$\eta_I = \frac{W_{net}}{m_{geo}(h_{in} - h_{rein})_{geo}} \tag{3}$$

$$\eta_{II} = \frac{W_{net}}{\dot{m}_{geo}[(h_{in} - h_{rein}) - T_0 \cdot (s_{in} - s_{rein})]_{geo}} \tag{4}$$

where the enthalpy and entropy of reinjected geothermal source is taken into account. In this section we will focus on a few binary geothermal energy conversion systems available in the literature with the aim of illustrating how the different option can be selected and the efficiency level of each of them.

The case studies selected include binary power plants of different types. In each case, an overall plant efficiency can be defined. From the analysis of the data available from literature it appears how First Law or thermal efficiencies typically lie in the range of 4–7%, while second law efficiency can be in the range 20-55%. In the matching processes, one has to consider the impacts not only on efficiency, but also on the environment, on the long-term pressure support and the geothermal resource availability. No standardization in the use of auxiliary working fluid is possible but the more commonly used are n-penthane. In a lot of the geothermal resource, the geothermal fluid comes in two phases. In a low to moderate enthalpy resource the steam quality is 10 to 30%.

2.2 General elements for the optimum design of binary cycle power plants

The process of design of a geothermal power plant can be considered as the typical optimum design problem involving a lot of design variables and parameters and a well defined constraint, represented by the geothermal fluid. This is generally characterized by a thermophysical conditions (pressure and temperature), chemical elements (composition of the fluid) and by an upper value of the mass flow rate that can be extracted from the geothermal reservoir to obtain “sustainable productions” (Sanyal, 2005).

The system involves three different sub-systems: the thermodynamic cycle, the recovery heat exchanger (RHE) in which the enthalpy of geothermal fluid is transferred to the auxiliary fluid, and the condenser and cooling system. Considering a geothermal heat source with certain characteristics (temperature, pressure, chemical composition and maximum mass flow rate that can be extracted), the problem is to match them with the working cycle and with the working fluid in order to obtain the best performance in energetic (exergetic) and economic terms.

But what matters most is the optimization of the whole system and to take into account the overall efficiency of the system it is necessary to consider the output net of parasitic power consumption, such as cycle pumps, production pumps, injection pumps, non-condensable gas extraction and mostly cooling systems power consumption. Most of the power cycles are optimized considering the maximum efficiency as the criteria, but different criteria can be taken into consideration. The maximization of efficiency can be considered equivalent to the maximization of net power produced per unit heat source mass flow rate

$$\beta_{geo} = \frac{W}{\dot{m}_{geo}} \tag{5}$$

or to the minimization of the mass flow rate of geothermal fluid for each unit power produced (“geofluid effectiveness”). But the thermal efficiency does not allow proper comparison of geothermal power plants. Other objective function can be considered as the net power produce per unit working fluid mass flow rate, if the point of view of the auxiliary fluid is considered

$$\beta_{aux} = \frac{W}{\dot{m}_{aux}} \tag{6}$$

This last parameter can be defined as “auxiliary fluid effectiveness”. Other possible design objectives take into consideration the ratio of the power produced and the total heat transfer surface of the recovery heat exchanger. If the pressure of the heater is less than the critical pressure, the heater (typically a shell-and-tube heat exchanger) is distinguished in two or three different sections: preheater, boiler and superheater. For this purpose and interesting merit parameter can be defined: the heater surface effectiveness defined as a kind of “heat transfer surface effectiveness”

$$\gamma = \frac{W}{A_{ECO} + A_{EVA} + A_{SH}} \tag{7}$$

As the ratio between the net power of the plant and the surfaces A of the sections (two or three) of the RHE: preheater (economizer), evaporator and superheater (if present) respectively. Another possible interesting objective of optimum design of a ORC power plant concerns the condenser; in case of wet cooling tower it can result is the availability of low-temperature cooling water or the net power produced per unit cold source mass flow rate (cooling water)

$$\beta_{CW} = \frac{W}{\dot{m}_{CW}} \tag{8}$$

This parameter is called “cooling water effectiveness”, while in case of air-cooled condenser in a typical binary geothermal power plant represents about 20 to 35% of the total plant cost. For this reason a new criterion for optimization can be proposed as the ratio of heat transfer area to net power produced.

$$\gamma' = \frac{W}{A_{COND}} \tag{9}$$

For the above exposed reasons, the problem of optimum design of a binary cycle air cooled geothermal plant can be considered as the typical multi-objective optimum design problem where it is not easy to define the objective function. Objectives of the optimization can be the maximization of the overall net conversion efficiency of the plant or the minimization of the cost of the plant. Since the cost of the heat exchanger and the condenser constitute a major part of the plant cost.

2.3 Binary cycle power plants worldwide diffusion

Mainly in the last ten years the perspective of installation of new binary cycle power plants has moved in a quite meaningful way the geothermal energy sector. More than 1050 MW of binary plants, corresponding to 78 new power plants has been installed in the ten years between 2005 and 2015 increasing the installed capacity from 738.9 MW up to 1790 MW (Table 1). The new plants have been installed mainly by a single manufacturer (ORMAT) even if a lot if new companies have approached the market and are present with a single installation (for example Exergy, EcoGen and Siemens) as better reported in Table 2.

Table 1: Binary cycle power plants installed

Period	Plants (units) installed [n]	Cumulative power [MW]
Before 2005	~200	738.9
2005-2009	27	465.8
2010-2014	51	585.3
Total	~280	1790.0

In the same period less remarkable installed capacity of flash-steam plants has been observed and only hundred additional MW installed of dry steam power plants is observed. The total amount of power plants installed up to now all over the world is less than 13000 MW.

Table 2: Main manufacturers and installations in the period 2005-2015

Manufacturer	Plants installed [n]	Cumulative power [MW]
ORMAT	45	821.6
Mafi-Trench	2	72
Atlas-Copco	2	48
UTC-Turboden	6	32.05
Turbine Air System	4	27.45

Even if geothermal power plants has the characteristics of operating for a lot of time (up to 8500 hours in a year), the total amount of installed power generation considering geothermal energy is well below the level of the other renewables.

Table 3: Installed capacity for the various categories of plants at the end of 2015

Location	Dry Steam	Single Flash	Double Flash	Triple Flash	Binary	Back Pressure	Hybrid	Total
Africa		543			11	48		602
Asia	484	2514	525		236			3758
Europe	795	796	273		268			2133
Latin America		908	510		135	90		1642
North America	1584	60	881	50	873		2	3450
Oceania		259	356	132	266	44		1056
	2863	**5079**	**2544**	**182**	**1790**	**181**	**2**	**12640**

3. ORC PLANT TECHNOLOGY: SOLUTIONS AND DESIGN PROBLEMS

Considering the installed power plants, binary technology represents today about the 15% of the total amount of the installed geothermal plants (Table 3). The main diffusion has been observed in the North America area even if interesting developments concerns Europe, Asia and Oceania too.

Analyzing in detail the various power plants, it is possible to understand that binary technology allows the use of low temperature water dominant reservoirs in the range of temperatures between 74°C (the case of Chena Hot Springs is a typical case study) and 160-180 °C. (Table 4). The perspective of using quite low temperatures makes geothermal power production feasible worldwide even for countries lacking high enthalpy resources at shallow depth reservoirs. For binary plants two different systems currently are state of the art, the Organic Rankine Cycle (ORC) and the Kalina Cycle, that has been considered an interesting solution, but is only marginally used. At the beginning of the development of the technology of ORC plants and for a quite long time, each installation has been designed for the conditions at a given location and the various systems have been tailored to specific geothermal fluid characteristics. Mainly in the last years attempts have been made by some manufacturers of providing “standard machinery”. Some manufacturers have proposed the use of standard systems and this approach could be the key element for a larger diffusion of small size geothermal plants. Unfortunately it is very difficult to pursue this objective for different motivations for different motivation concerning both the nature of the geothermal resources and the environmental conditions, that have importance for the definition of the condensation temperature. The temperature of the condenser in geothermal power plants may have different values depending on its location in the world.

Table 4: Binary plants installed before 2005

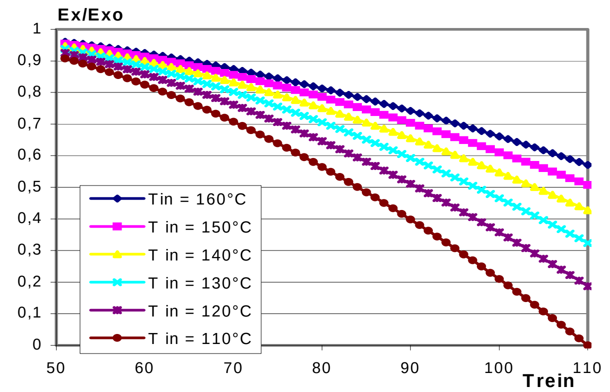
Country	Plant	Power installed	Date
USA	Wabuska	2.2	1984
USA	Casa Diablo	40	1984
USA	Wineagle	0.7	1985
USA	Steamboat	35.1	1986
USA	Soda Lake	3.6	1987
Thailand	Fang	0.3	1989
USA	Ormesa	68	1987-89
Cina	Nagqu	1	1993
USA	Heber		1993
Mexico	Los Azufres	3	1993
Philippines	Makiling-Banahaw	15.7	1994
Portugal	Ribeira Grande	13	1994
New Zealand	Northland (Ngawha)	10	1997
Australia	Bad Blumau	0.2	2001
Austria	Altheim	1	2002
Nicaragua	Momotombo	7.5	2002
Germania	Neustadt- Glewe	0.2	2003

Indeed, the climate around a geothermal power plant dictates the outdoor temperature, which then dictates the temperature in the condenser.

3.1 The definition of reinjection temperature

In most of the actual cases, the perfect match between the geothermal source and the thermodynamic cycle, above is not feasible, mainly because of limitation in the reinjection temperature of the geothermal fluid. Really the power potentially extractable from a geothermal reservoir can be directly correlated to the temperature difference rather than to the temperature of the reservoir and exergy potential rather than energy (enthalpy) is important in order to define the potential of the reservoir.

While the enthalpy of a geothermal resource can be considered approximately as a linear function of the temperature, the exergy potential strongly depends on the permissible value of the reinjection temperature (T_{rein}). The reinjection temperature strongly depends on the scaling potential of geothermal fluid, that must be separated at a temperature high enough to avoid solid deposition. Salt deposition and related phenomena are a major constraint on the development of geothermal energy worldwide. Among the different minerals susceptible to deposition, silica and calcite are the most common. Even in small concentrations, silica affects steam turbines, valves, and separators and can cause extensive fouling in the heat exchanger, and to reinjection gathering pipelines.



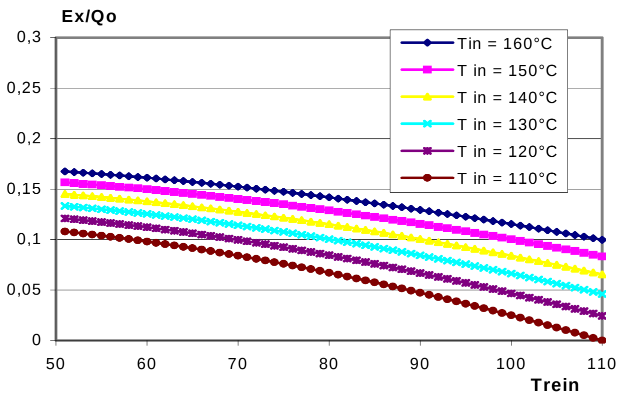


Figure 4: dimensionless parameters for classification of geothermal sources

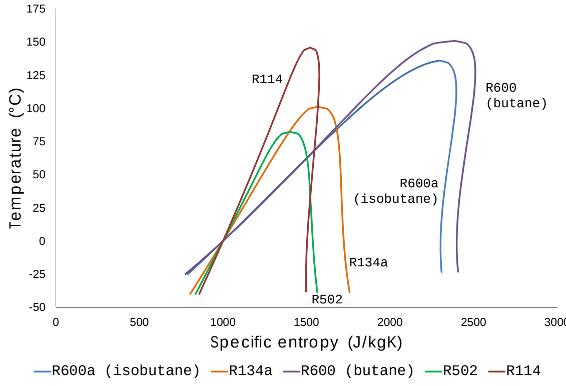


Figure 5. Available working fluids for ORC cycles and thermophysical properties

The prospect of silica deposition after separation of two phase geofluids inspired a conservative approach to the design of geothermal power plants so that the difference of temperature between the geothermal source T and a reference temperature T_0 is important.

3.2 Selection of working fluids and thermodynamic optimization of the heat recovery cycle

In a binary power plant, the working fluid runs in a closed circuit according to a thermodynamic cycle between two heat sources, water at high temperature and cooling water or cooling air. The thermodynamic properties of the working fluids are considered as key parameters. The selection of suitable fluids for use in binary cycle plant is a quite complex problem and cannot be disjointed by the heat recovery cycle selected. In general fluid deserves the following characteristics: low critical temperature and pressure, small specific volume, low viscosity and surface tension, quite high thermal conductivity, suitable thermal stability and environmental acceptability.

A desirable thermodynamic property of the fluid is a near vertical saturated liquid and vapor line for the possibility of “carnotizing the cycle" but this is a quite complex question. The saturation vapor curve is the most crucial characteristic of a working fluid in an ORC. This characteristic affects the fluid applicability, cycle efficiency, and arrangement of associated equipment in a power-generation system.

There are two types of vapor saturation curves in the temperature-entropy (T-s) diagram: dry fluids with positive slopes (dT/ds), wet fluids with negative slopes (Fig. 5). In the second case, since the vapor expands along a quite vertical line on the T-S diagram, vapor saturated at the turbine inlet will remain saturated throughout the turbine exhaust it seems not particularly convenient to resort to Rankine cycle with superheater. The performance may be improved by adopting multi-component mixtures. Multi-component mixtures have been developed recently to achieve better matching of working fluid and source heat capacities. In optimizing binary cycles, the potential advantages of using non-azeotropic mixtures to achieve non-isothermal phase changes and to obtain Kalina cycle have been recognized.

For this aim an important criteria to optimize an ORC is the minimization of the exergy loses related to the recovery heat exchanger (RHE); this can be obtained theoretically by increasing the number of pressure levels (PL) of the thermodynamic cycle. A complete analysis of the system involves the evaluation of exergy loses in the steam turbine as well as the residual exergy of the auxiliary working fluid at the end of expansion. The residual exergy of the geothermal brine at reinjection temperature are important element too. The exergy balance is:

$$E_{geo} - E_{rej} = W_{net} + W_{par} + I_{RHE} + I_{ST} + I_{Cond} \quad (10)$$

One of the most important aspects is the design of the binary cycle power plants is the RHE, that represent the connection between the geothermal fluid loop and the thermodynamic cycle. Considering the quite low temperature of the geothermal fluid, possible options for the heat recovery cycle can be represented by 1PL (both Rankine cycle and Rankine cycle with superheater) or 2 PL (with coupled or uncoupled turbines) (Fig. 6).

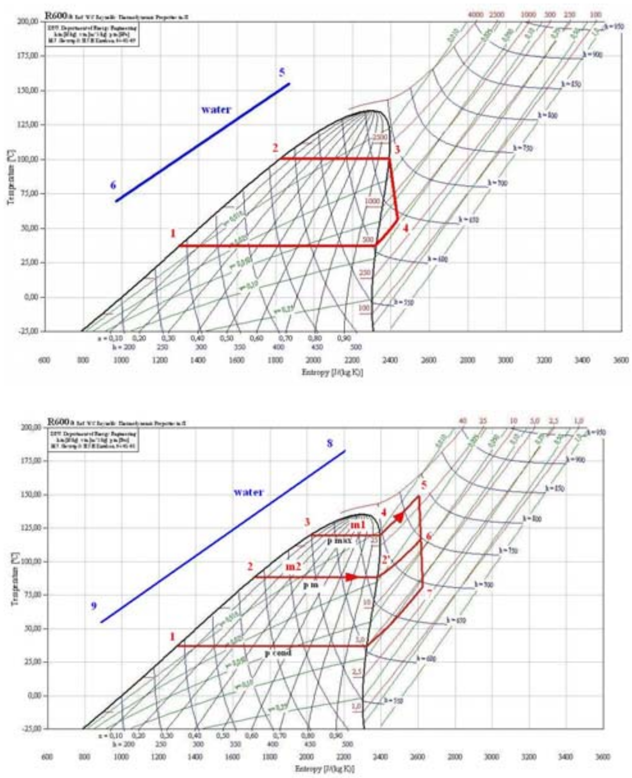


Figure 6. Two different kind of RHE (a) Rankine cycle and (b) Two pressure level RHE

Some authors propose the use of supercritical cycles with regeneration. They state that this is theoretically the ideal cycle for geothermal power generation. But this is true only in the perspective of stability of geothermal source and of the environmental temperature.

Anyway, it is possible to state that a good match between thermodynamic cycle and working fluid can be obtained for each kind of combination so that the influence of the working fluid can be considered marginal in the field of the optimization of ORC performances. For this reason, as it will be discussed in the further section, in some cases the working fluid choice is driven by economic or supply-oriented evaluations by end-users. So more complex elements could be added to this thermodynamic optimization.

3.3 The problem of heat exchangers and auxiliary systems sizing

When power is recovered from low temperature heat sources, due to the quite low value of the First Law efficiency relatively large values of heat exchanger areas and circulation flow rates heat source, working fluid and cooling water are necessary. This impacts in particular on heat transfer devices such as condenser, preheater and evaporator, and the cost of these devices largely contributes to the total power plant cost increase. This is mainly true for the condenser surface in case of dry type cooling towers. In this case even if no water supply is necessary, regarding auxiliary power consumption, they usually consume much electricity than wet cooling towers (this determines a reduced power output of the plant), moreover, due to the need of higher heat exchange surface and of a large volume of air that has to be moved through them, the condenser section costs about 5-10 times as much as a wet type one, depending on the condensing temperature of the turbine, mainly if low condensing temperatures are considered (as minimum approach against environmental temperature decreases). So a suitable selection of operating conditions (condenser temperature and ambient temperature) of the plant and an optimum thermal design of the heat transfer surfaces is necessary for optimum design problem.

3.4 Increase of turbine (expander) efficiency and new turbine concept

Increase in the turbine efficiency (through continuous improvements in thermo-fluid-dynamic, finite element and vibration analysis) is object of the research too.
Titanium blades have been developed by some leading manufacturers in the industry, displaying improved corrosion resistance. However these have not gained widespread acceptance due to concerns about their performance in relation to erosion resistance. At the opposite end of the spectrum, there is reputedly intriguing ongoing work to develop small, 'high speed' turbine wheels that rotate at tens of thousands of RPM a concentrated power extraction. Clearly the benefits here would be reductions in materials usage, although questions remain about use of such devices with wet steam that would cause erosion. Recently, within the indirect geothermal market (i.e. non flash) such turbo-expanders are commonly used with binary fluids.

4. THE PESPECTIVES OF BINARY CYCLE POWER PLANTS IN GEOTHERMAL ENERGY INDUSTRY

In the technical field of ORC technology the recent evolution of the research, slightly evidenced in this paper, mainly deal with a lot of topics that are summarized in the following lines:

- Working fluid chemical studies and stability
- Plants layout and compact configuration
- Combined plants optimization
- Thermal cycle definition
- Supercritical cycles configuration
- Machinery optimization
- Exergetic analysis
- Thermoeconomic and exergonomic analysis
- Optimization engineering
- Dynamic analysis
- Hybrid systems
- EGS systems exploitation
- Plant equipment design

The interest in the filed of the binary cycle power plants and ORC technology is clearly identified by the large amount of scientific contributions in this field. About 900 papers can be found in the most used research journal collector (www.sciencedirect.com), 154 of which produced in the first half of 2016.

As the development of the geothermal ORC industry has been illustrated in the previous sections, some considerations on its evolution and industrial trends must now be individuated. Often, in the common activity the thermodynamic optimization, the results are impacted by practical issues and by constraints individuated by Institutions, customers, and all of these are case specific. These constraints are apparently contrasting with the necessity of standardization (e.g. size, equipment selection, encironmental issues).

4.1 Fluid selection and cycle definition

The fluid selection, and in particular the cycle optimization function, can have different targets, as it has been illustrated in the previous sections, and as it is available from the specific recent literature. The working fluids available on the market can match with the main design needs (temperature interval, chemical stability, environmental impact, enthalpy useful interval at expansion). In such cases also other constraints can impact on the fluid selection. Refrigerant fluids can have specific costs which are not competitive with the hydrocarbons. Hydrocarbons (like for example pentane, butane, and their isomers) are derived products from the oil and gas industry, easier to be supplied, differently from more evolved and synthesis derived chemicals.

Refrigerants can somehow have law constraints about their utilization, as they can have ozone depleting potential and greenhouse effects no more acceptable from many country law and standards. For this reason some refrigerants are being neglected, foreseeing their phase-out from markets and operation in many countries. In any case, refrigerants could appear, mainly to the local communities, such less dangerous fluids for ORC applications, as many of them are not flammable or explosive.

The phase-out procedures (European Commission proposal, 2012) are leading the chemical production companies to individuate substitute fluids for the ones which are not eligible for law constraints (Invernizzi et al. 2016). This factor lead the specific costs to increase, as the cost must comprehend the research and new market introduction efforts. As the fluid choice and cycle parameters definition can then be optimized in many ways, according to thermodynamic and technical targets, often it can occur that more practical and site specific factors have a heavier weight on business decision.

4.2 Scaling and material selection

As it has been addressed from research and technical applications, scaling is one the more impacting issues in the design of binary cycle power plants. Scaling problems, mainly connected to silica scaling is directly connected with the chemical composition of the fluid. Its peculiarity is that it can only be foreseen basing on previous experience, which is lacking when facing a new developing reservoir, with no drilling historical data. Its real impact can be measured only when the wells are drilled and a dedicated analysis is performed. Scaling and deposition problem are currently being faced through experience and background of operators, and it is one of the sectors less involved in technology transfer of this field.

4.3 Incentives and country specific constraints

Geothermal ORC industrial sector is growing up in many countries, as it has been addressed by the previous sections. It is practically the only real driver of the geothermal market, on a large scale, as combined cycles and more traditional flash and direct expansion plants do not have the same grow trend.

In many countries, governments and local authorities are trying to subsidize ORC applications. The model of the “pilot plants”, for example, is now under development in Italy (where geothermal exploitation for electrical energy production has been first applied). In other countries the exploitation of undeveloped reservoirs is occurring also under institutional roadmaps and incentives. This is surely going in the direction of exploiting the geothermal resources which are more distributed worldwide and not yet under development. One concern can be individuated somehow, as the research trends and technical innovation have not the same timescale of the country and local implementation. In ORC geothermal application the technology transfer is being an issue, as not all the institutions are aligned with the research evolution. The geothermal market could be somehow impacted by this lack of technology transfer, although the research and papers on these topics has increased in the last years.

4.4 Sustainability issues

With all these factors standing on the business decisions, it is often difficult to identify the interfaces between the different industrial backgrounds, in order to maximize the sustainability of the whole project, also considering the "plant-reservoir" system (Franco and Vaccaro 2012, 2014).

An extended definition of "geothermal system" can be given: which should comprehend the power plant but also the utilization facilities, the wells, the reservoir and the groundwater circulation system together with the environment (Franco and Vaccaro, 2012). In this perspective, some development driving factors are not always oriented to the best sustainability pathway for the specific reservoir. For example, in same cases the Institutions use to incentive the extracted geofluid flow rate, while in some other cases (e.g. "pilot plants" in Italy) a standard minimum plant size should be targeted in order to reach incentives.

5. CONCLUSIONS

Geothermal ORC power plants are considered today as the most important driver technology in the development of the geothermal energy industrial branch. This is evident from the evolution of the market and from the plant data installation about new units, observing the development in the last ten years. A lot of new plants, often installed in countries not involved before in geothermal energy field. The development of several new plants based on the concept of the Combined cycles (e.g. flash cycle with bottoming ORC unit) are another important factor for the development of this industry, mainly when an existing traditional plant exists or in the case of newly medium-high enthalpy reservoirs exploitation.

By analysing the recent technological advancement and research trends, it appears that more industry-related factors are affecting the business decisions in this field rather than energetic optimization processes and technical innovation, here synthesized and illustrated by the existing literature. The perspective of innovation of the thermodynamic cycle basing on supercritical, transcritical or Kalina cycles appears to be confined in the scientific literature and minimum has been the effect on the real applications.

In particular, the fluid selection has always been an issue, considering the thermodynamic issues related to Second Law Efficiency of specific fluid consumption factor. In many cases, regulation or cost driven decision can move the design specifications from the thermodynamic optimum point. Scaling and solid deposition phenomena and Institution incentive rules have a strong impact on the decisional process too. As scaling and solid deposition phenomena can not always be foreseen in the previous phases of a geothermal project.

Anyway, the overall sustainability of a project in the field of ORC plants, at the end, seems to be affected by heterogeneous factors, all of them important if considering profitability of the project, but not always technically related to the geothermal elements, for example the geofluid characteristics and this made difficult to identify a clear perspective of development for geothermal plants based on binary cycle technology.

In the meantime, the perspective of development of plants based on standard machinery, seems to be difficult to pursue and this is one the motivation of the difficult development of geothermal energy referred to medium to low enthalpy resources.

REFERENCES

Astolfi, M., Romano, M.C., Bombarda, P. and Macchi, E.: Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium–lowtemperature geothermal sources—part A: thermodynamic optimization. Energy 66, (2014), 423–434.

Bertani, R.: World Geothermal Generation 2001-2005: State of the Art, *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, (2005), paper # 0008.

Bertani, R.: Geothermal Power Generation in the World 2005–2010 Update Report, *Proceedings of the World Geothermal Congress 2010*, Bali, Indonesia, (2010), paper # 0008.

Bertani, R.: Geothermal Power Generation in the World 2010-2014 Update Report, *Proceedings of the World Geothermal Congress 2015*, Melbourne, Asutralia, (2015), paper # 01001.

Chagnon-Lessard, N., Mathieu-Potvin, F. and Gosselin L.: Geothermal power plants with maximized specific power output:Optimal working fluid and operating conditions of subcritical andtranscritical Organic Rankine Cycles, Geothermics 64 (2016) 111–124

DiPippo, R.: Geothermal power plants: Principles, applications, case studies and environmental impact; 2nd edition. Butterworth-Heinemann, New York, NY, USA, (2008), 493 pp.

Drescher, U. and Brüggemann, D.: Fluid selection for the Organic Rankine Cycle(ORC) in biomass power and heat plants. Applied Thermal Engineering 27, (2007), 223–228.

European Commission Proposal for a Regulation of the European Parliament and of the Council on fluorinated greenhouse gases. (2012). 2012/0305. http://ec.europa.eu/clima/policies/f-gas/legislation

Franco, A.: Power production from a moderate temperature geothermal resource with regenerative Organic Rankine Cycles. Energy for Sustainable Development, 15 (2011), 1-9.

Franco, A. and Vaccaro, M.: An integrated "Reservoir-Plant" strategy for a sustainable and efficient use of geothermal resources, Energy, 37, (2012), 299-310.

Franco, A. and Vaccaro, M.: A combined energetic and economic approach for the sustainable design of geothermal plants, Energy Conversion and Management, 87, (2014), 735-745.

Franco, A., Villani, M.: Optimal design of binary cycle power plants for water-dominated, medium-temperature geothermal fields. Geothermics; 38 (2009), 379–391.

Gnutek, Z. and Bryszewska-Mazurek, A.: The thermodynamic analysis of multicycle ORC engine. Energy; 26 (2001), 1075-1082.

Hung, T. C.: Waste heat recovery of Organic Rankine Cycle using dry fluids. Energy Conversion and Management 42 (2001), 539–553.

Huttrer, G.W.: The status of world power generation 1995-2000, *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, (2000), paper # R0637.

Invernizzi, C.M., Iora, P., Preßinger, M. and Manzolini, G.: HFOs as substitute for R-134a as working fluids in ORC power plants: A thermodynamic assessment and thermal stability analysis, *Applied Thermal Engineering*, Volume 103, (2016), 790–797.

Kanoglu, M.: Exergy analysis of a dual-level binary geothermal power plant. Geothermics; 31, (2002) 709-724.

Kose, R.: Geothermal energy potential for power generation in Turkey: A case study in Simav, Kutahya. Renewable and Sustainable Energy Reviews 11, (2007) 497-511.

Madhawa Hettiarachchi, H.D., Golubovic, M., Worek, W.M. and Ikegami, Y.: Optimum design criteria for an Organic Rankine Cycle using low-temperaturegeothermal heat sources. Energy 32, (2007), 1698–1706.

Pan, L. and Wang, H.: Improved analysis of Organic Rankine Cycle based on radialflow turbine. Appl. Therm. Eng. 61, (2013), 606–615.

Povarov, O., Saakyan, V., Nikolski, A., Luzin, V., Tomarov, G. and Sapozhnikov, M.: Experience of creation and operation of geothermal power plants at Mutnovsky geothermal field, Kamchatka, Russia, International Geothermal Conference, Reykjavík, (2003).

Sanyal, S.K.: Sustainability and Renewability of Geothermal Power Capacity, Proceedings of the World Geothermal Congress, Antalya, Turkey (2005).

Stefansson, V.: World geothermal assessment. *Proceedings of the World Geothermal Congress* Antalya, Turkey, April 24-29, (2005).

Wang, X., Liu, X. and Zhang, C.: Parametric optimization and range analysis ofOrganic Rankine Cycle for binary-cycle geothermal plant. Energy Conversion and Management 80, (2014) 256–265.

Zarrouk, S.J. and Moon H.: Efficiency of geothermal power plants: A worldwide review, Geothermics 51 (2014) 142–153.