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Design strategy of geothermal plants for water dominant medium-low temperature reservoirs based on sustainability issues

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Abstract

A design strategy based on a multidisciplinary approach for a sustainable design of ORC power plants is proposed. The design of a geothermal plant is discussed, with reference to a case study about a geothermal area in Tuscany, in which a geothermal reservoir at 120 °C is estimated to be available at about 500 m of depth. A qualitative model of the reservoir under specific production/reinjection conditions is discussed.
Numerical simulation of geothermal reservoirs is considered an important interacting issue, also to synthesize the data and different scenarios studied. Three factors are fundamental: the maximum energy production, in the perspective of a sustainable exploitation strategy (definition of wells depth and siting, fluid rates extracted/reinjected); the chemical characterization of the fluid (to define the minimum reinjection temperature in order to prevent scaling phenomena); the definition of a reinjection strategy (flow rates, number and depths of reinjection wells and distances between them).
Key results are the temperature and pressure profiles and stored energy reduction in the reservoir during plant lifetime. A power plant output range of 250 – 500 kW is considered in order to keep the temperature decrease in the reservoir in a range of 5 - 10 °C during the expected life of the plant. The case study can be seen also as a general value example to discuss how the sustainability of the medium-low temperature geothermal resource makes the design strategy of these plants different with respect to the other renewable source based power plants.

Keywords:
Geothermal energy, Sustainability, Binary cycle power plants, Medium temperature geothermal field.

1. Introduction

The great part of geothermal resources available around the world are water dominated fields, at temperatures under 150 °C and pressures below 15 bar [1]. The total worldwide expected geothermal potential for power production has been estimated being about 200 GW, [2]. The binary cycle technology using Organic Rankine Cycle (ORC) is the most efficient solution for power production from these fields. Some manufacturers (Pratt & Whitney/UTC, Siemens) have proposed small size (0.2 MW) standard machinery and power conversion systems. This can be a key element for a large diffusion of geothermal binary cycle plants. The size and peculiarity of such plants is often different from the industrial practice of power production from renewable energy sources. Sustainability and operational parameters of the resources become fundamental issues for these utilizations, to guarantee a successful productivity of the power unit and maximize the durability.

Medium-low enthalpy geothermal resources can be available, in many areas, at relatively low depth (less than 1000 m). This circumstance allows a meaningful reduction of drilling and perforation costs on the total cost of the plant. A simulation of the geothermal reservoir and the time variations of temperature and pressure under exploitation conditions should be carried out before the design of the plant, mainly in case of ORC units utilization. This is heavily important for reservoirs at temperatures below 130 °C. Small size power plants (100 kW – 5 MW) are innovative since in traditional geothermal power industry almost only greater sizes (5-200 MW) have been used (flash systems, dry steam plants). Medium-low temperature resources, to be exploited for power purposes with ORC systems, introduce the possibility of small size units. Project sustainability, durability of the plant and low environmental impact of this technological solution are advantageous key points, although the exploration and characterization phases will assume a huge importance. As their performances are strongly affected by changes in the external parameters (resource, environment), a reliable characterization process needs to be carried out, in order to avoid unacceptable off-design working points.

A multidisciplinary approach to geothermal projects is necessary. The interconnections between Geosciences and Energy Engineering backgrounds have been diffusely remarked, in the perspective of geothermal plants development and diffusion [3].

The main task of the geothermal utilization projects is the sustainable utilization of the reservoirs and the maximization of the durability of the resource (mainly in terms of temperature and pressure). For this reason it is very important to consider and analyze the whole *"geothermal system"* constituted by the power plant, the wells system, the geothermal reservoir and all the links between them and the environment.

The key factors governing the optimization process of the design of a plant are the definition of a sustainable mass flow rate extraction (potential assessment) and the reinjection strategy (taking into account the scaling phenomena) [4], [5]. Typical problems due to an incorrect characterization of the resource available are:

- oversizing of the plant, causing excessive extraction of fluid (the reservoir doesn't replenish the energy stored);
- unacceptable scaling phenomena (causing corrosion, productivity drop, net diameter reduction, damaging);
- excessive cooling of the reservoir or losses of fluid due to wrong reinjection strategy.

Numerical simulation of geothermal reservoirs is considered to be a very useful and strategic instrument both for two main tasks in the power production industry: the history matching of the field data (from the exploration/utilization history) and the forecast about exploitation scenarios. Its reliability depends on the accuracy of the input data (a tough problem is the definition of a reliability scale for decision making about production).

In this study the design of a geothermal plant is discussed, with reference to a case study: a geothermal area in Tuscany, in which a geothermal reservoir at about 120 °C is estimated to be available (at a depth of about 500 m). The optimal production/reinjection and global design strategy for a small size ORC based power plant is discussed.

2. Low-temperature geothermal technology and binary cycle power plants

Medium to low temperature geothermal resources are largely diffused, so that they have become very attractive for electrical power production in the last years. According to the more significant approaches in the literature, the classification of the geothermal resources depends mainly on the temperature value. In Table 1 a classification of the geothermal resources is provided. It is estimated that the major part of the geothermal energy stored worldwide is available at temperatures lower than 150 °C [1-2]. Those resource become particularly interesting when they are available at depths below 1000 m.

Table 1. Classification of the geothermal resources depending on temperature [°C]

	Muffler & Cataldi [6]	Hochstein [7]	Benderitter & Cormy [8]	Nicholson [9]	Axelsson & Gunnlaugsson [10]
Low enthalpy	< 90 °C	< 125 °C	< 100 °C	≤ 150 °C	≤ 190 °C
Medium enthalpy	90 – 150 °C	125 – 225 °C	100 – 200 °C	-	-
High enthalpy	> 150 °C	> 225 °C	> 200 °C	> 150 °C	> 190 °C

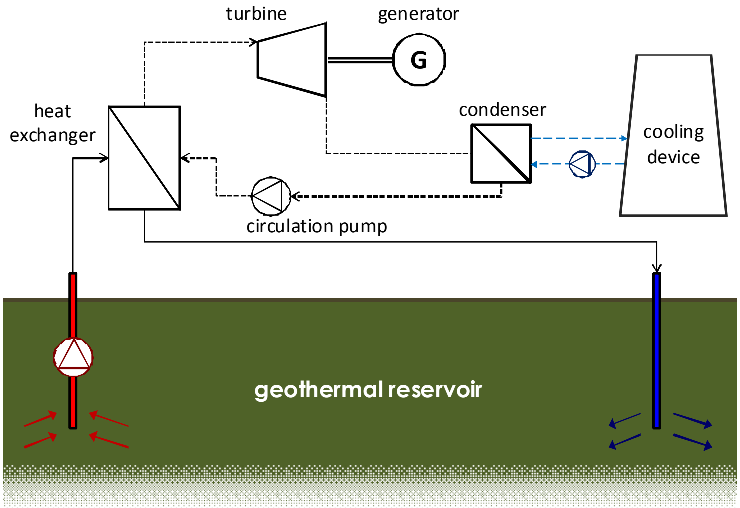


Fig. 1. Scheme of a ORC unit working on a geothermal reservoir, a doublet of withdrawal-reinjection wells is shown

Binary power plants based on Organic Rankine Cycle (ORC) are considered to be the best technology to exploit medium-low geothermal resources (mainly water dominated) at temperature below 180 °C. The operating principle of this plant is represented in the scheme of Fig. 1.

In a binary cycle power plant the heat of the geothermal fluid rate is transferred to a secondary working fluid (usually an organic fluid with a low boiling point than water at a given temperature) through an heat exchanger. The cooled geothermal fluid is then returned to the ground to recharge the reservoir, while the working fluid expands through a turbine, producing electrical power and then is condensed by exchanging heat with the environment (dry or wet cooling).

A geothermal binary power plant is characterized by high brine specific consumption β (kg of fluid extracted per unit of power produced) and low First Law efficiencies η_I (5-10%), even if Second Law efficiencies η_{II} are typically in the range 25-45%. They usually require large heat transfer surfaces both for the recovery heat exchanger and for the condensation system. The parasitic power consumption of this auxiliary system is relatively high because of the need for forced ventilation. A dry cooling system can absorb from 10-12% of gross power (under ideal conditions) to as much as 40-50% if the ambient temperature is very close to the condensation temperature. A diffused literature about this technology is available, often based on specific and local industrial application. The efficiencies of binary cycle plants are very sensible to the external thermodynamic parameters (ΔT of fluid, environmental temperature, fluid pressure, permeability changes), so the characterization of the resource available is a fundamental step.

Recently, binary power plants have been installed in Austria and Germany in applications to medium-low temperature geothermal sources (Bertani [11]). Various studies ([12-14]) demonstrates the relevance of the optimization process applied to ORC units, particularly in terms of efficiencies and fluid extraction. These plants often operate through advanced thermodynamic cycles (dual pressure level Rankine cycle or Kalina cycle) and may also use different or unconventional working fluids, such as ammonia-water mixtures (e.g. Husavik, Iceland). The characteristics of some of those plants are given in Franco [15], in which a table collecting a series of available data is present. The temperature range covered is wide (74-124 °C) so that specific brine consumption lies in the range from 44 to 200 kg/s for each MW of electricity produced.

The remarkable difference among the various plant performances can be explained in al lot of case because of the different temperature interval ($\Delta T = T_{geo} - T_{rej}$) available between the reservoir and the reinjection temperature. A scheme of temperature values of different plants is given in Fig. 2.

Till some years ago each installation was designed for specific conditions at a given location. Every system is generally tailored to specific geothermal fluid characteristics, while the medium and low temperatures applications permit to pursue the perspective of providing “standard machinery”. The possibility of “standard machinery” development is submitted to a proper characterization and potential assessment of each local reservoir, due to the strong dependence on β, η_I and η_{II} from external parameters (environment/reservoir).

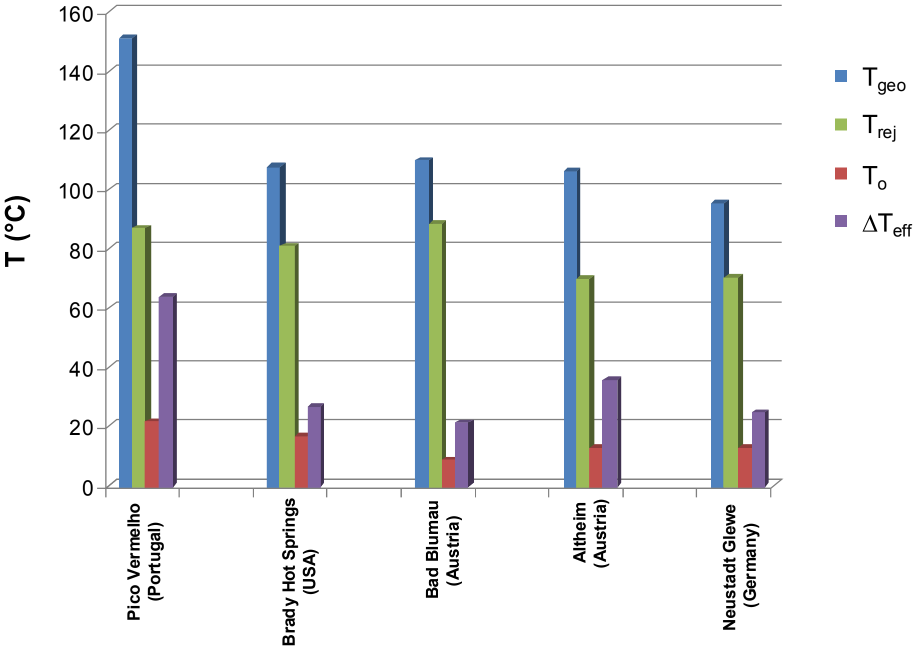


Fig. 2. Temperature values (production – reinjection – environment) in some binary plants.

2.1 Geothermal potential assessment and binary plants

A general methodology for the Geothermal Potential Assessment for every kind of geothermal field doesn't exist, although in literature a lot of different methods and reliable principles have been treated and tested, ([4], [6], [10]). Several studies are about specific geographical areas, more than general value survey and investigation techniques. A lot of instruments are available today to improve the detail of the information needed for the sustainable design of plants.

The geothermal potential of a particular area means particularly the definition of temperature (T_{geo}) and pressure (p_{geo}) of the geothermal fluid and of the maximum mass flow rate ($\dot{M}_{geo}$) that can be extracted maintaining for a long time the thermal properties of the reservoir.

A brief list of the general results that should be evaluated is here proposed: thermal energy stored (at a certain time) in the reservoir; temperature, pressure and rate of the extracted fluid; chemical composition of the fluid and saltiness (to define the reinjection temperature T_{rej}); number of wells to be drilled and mutual distances between them; time interval to have an appreciable decrease in the rate and temperature of fluid (or productivity); definition of both the "Base" resource available and of the "Effective" resource, which is useful under favourable and sustainable (economic-environmental-technological) conditions, [6]; siting of the reinjection wells (number, mutual distances and interference effects); reinjection strategy (effects of reinjection on productivity); number of wells for compensation. The total energy available is the portion extractable and favorably useful of the stored energy in the reservoir. It can be defined roughly multiplying the total energy stored for an appropriate recovery factor (R), [6]. The estimation of the recovery factor is not a trivial task, it depends from the site characterization and it can also be a result of assessment according to the individuals experience.

Let us now consider a water dominated geothermal field at moderate temperature. The energy potential of a geothermal reservoir can be first of all referred to the available temperature of the aquifer (T_{geo}). In the case of water dominated geothermal fields, the energy available can be referred to an equivalent specific thermal capacity of the reservoir (both rocks and fluid), namely $\varepsilon_{(T_{geo}-T_0)}$, which can be defined referring to the cooling down to a low temperature level, in this case the environmental temperature T_0.

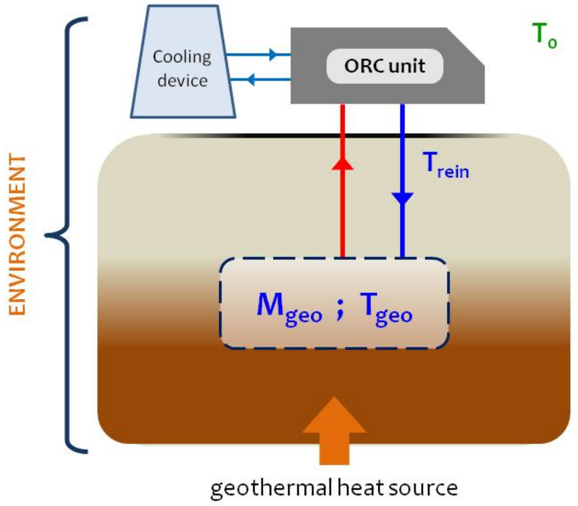


Fig. 3. Sketch of a "geothermal system" for which a geothermal potential can be defined

So if reinjection is considered, as in almost all the geothermal projects today, the useful temperature difference is $\Delta T = \left(T_{geo} - T_{rej}\right)$, being $T_{rej} < T_0$ (see Fig. 2). This means that a mass flow rate higher than $\dot{M}$ should be extracted for power production, according to the upper limit given by

$$\dot{M}^* \cdot c_p \cdot \left(T_{geo} - T_{rej}\right) \leq \dot{M} \cdot \varepsilon_{(T_{geo} - T_0)} \tag{1}$$

It is important to understand that the upper limit for the energy potential is a function of the whole "geothermal system", as defined in the Introduction and remarked in Fig. 3

$$\Pi = f\left(geothermal\ \ system\right) \tag{2}$$

The meaning of the last two equations is that, for a given value of maximum energy potential and for a given value of ΔT, a maximum value of mass flow rate (extracted/reinjected), M^*, can be defined. M^* clearly depends on a lot of parameters and factors (both natural and technological): permeability distribution; hydraulic linking between the production and the reinjection areas; siting of the wells; natural recharge (meteoric water) to the reservoir.

Due to the presence of this upper limit it is clear that the value of ΔT used is inversely proportional to the value of M^*. So in case of T_{rej} increasing, induced by unacceptable chemical deposition phenomena, the mass flow rate $\dot{M}$ increases, and it could reach excessive values, causing unwanted cooling down of the whole aquifer. Consequently each reservoir presents an optimal combination of mass flow rate extractable and reinjection temperature and a correct design should follow this rule.

As it can be seen, this optimization problem involves the whole "geothermal system" (plant, reservoir, environment and their mutual links), so a multidisciplinary approach become necessary.

The difference between the temperature of the reservoir (T_{geo}) and the reinjection temperature (T_{rej}), together with the geofluid availability ($\dot{M}_{geo}$ in the following, being equivalent to $\dot{M}$) and the environment reference temperature (T_0) contribute to define the exergy and energy potential of the geothermal field. The power production available from a plant can be defined according to the law

$$W_{net} = \eta_I \cdot \left[\dot{M}_{geo}(h_{geo} - h_{rej})\right] \approx \eta_I \cdot \left[\dot{M}_{geo} \cdot c_{p,geo}\left(T, p\right) \cdot (T_{geo} - T_{rej})\right] \tag{3}$$

where η_I is the First Law Efficiency of the plant, that is a complex function of the temperature difference (T_{geo}-T_{rej}), of the condensation temperature (strongly influenced by the environmental temperature) and of the particular Organic Rankine Cycle (ORC) used in the binary plant. Considering the specific enthalpy of the geofluid η_I can be defined as follows

$$\eta_I = \frac{W_{net}}{\dot{M}_{geo}(h_{geo} - h_{rej})} \tag{4}$$

2.2 Binary power plant design and performance parameters

An important performance parameter for the analysis of the geothermal plant is the mass flow rate to generate a fixed power output, or specific brine consumption, which is given by:

$$\beta = \frac{M_{geo}}{W_{net}} \tag{5}$$

It is inversely proportional to the First and Second Law Efficiency, which are defined as

$$\eta_I = \frac{W_{net}}{\dot{M}_{geo} \cdot \left(h_{geo} - h_{rej}\right)} \tag{6}$$

$$\eta_{II} = \frac{W_{net}}{\dot{M}_{geo} \cdot e_{geo}} = \frac{W_{net}}{\dot{M}_{geo} \cdot \left(h_{geo} - T_0 s_{geo}\right)} \tag{7}$$

Previous studies, [3-4] show that the specific brine consumption strongly depends on the difference between reservoir temperature (T_{geo}) and reinjection temperature (T_{rej}), varying from 25-40 kg/s for each MW produced in case of source temperature of 150-160 °C, up to over 100 kg/s for each MW produced in case of $T_{geo} = 110\ °C$. Due to the medium-low specific enthalpy entering the heat exchanger, this typical values of flow rate have to be considered in terms of design parameters and costs, particularly for small size power plants. The output power depends mainly by the thermodynamic cycle typology of the secondary fluid. Considering the schemes of Fig. 4 and 5 it is

$$W_{net} = W_{gross} - W_{pump} - W_{CS} = m_{w-fluid} \left[\Delta h_{esp} - \frac{v_{w-fluid}\left(p_{sat} - p_{cond}\right)}{\eta_{pump}} \right] - W_{CS} \tag{8}$$

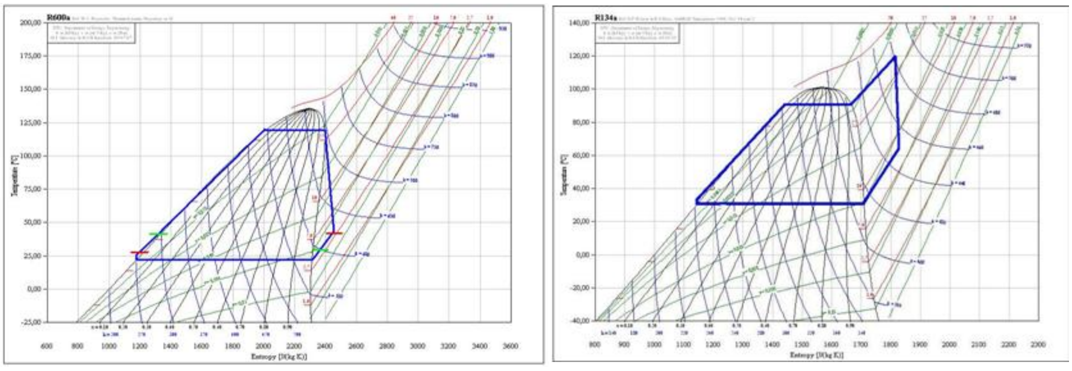
$$m_{w-fluid}\left(h_3 - h_1\right) = M_{geo}\left(h_{geo} - h_{rej}\right) \tag{9}$$

A limited reduction of the temperature of the geothermal source from T_{geo} to $T^* < T_{geo}$, can be compensated by an increase of the mass flow rate extracted. This is possible if the balance

$$\dot{M}^*\left(h^* - h_{rej}\right) = \dot{M}_{geo}\left(h_{geo} - h_{rej}\right) \tag{10}$$

can be maintained even if there is a decline of temperature and pressure in the reservoir, because

$$h^* - h_{rej} \approx c \cdot \left(T^* - T_{rej}\right) \tag{11}$$



(a) (b)

Fig. 4. Thermodynamic cycles used in binary power plants (fluids R600a and R134a)

A temperature reduction of the geothermal source could cause the end of life of the plant because it could be impossible to maintain a correct pinch-point value in the heat exchanger (in Fig. 5 the decrease of the rejection temperature profile, caused by a decrease of the source temperature, cause a decrease of pinch point from the value *PP1* to the value *PP2*). This problem is important for each typology of ORC, but in particular with reference to advanced heat recovery solutions, like Rankine with superheater, Kalina and Supercritical cycles and for $T_{geo} < 120\text{-}130\ °C$.

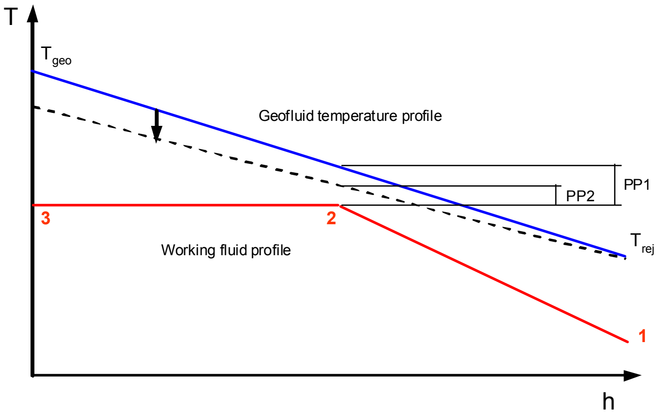


Fig. 5. Temperature profiles trend in the heat exchanger of a binary plant

3. Design strategy for binary cycle power plant

The methodology proposed has the purpose of defining peculiar targets which are characteristic of small size ORC technology. Geothermal resource is totally renewable only under particular conditions, that have to be assured by a sustainable conception of a geothermal utilization project. One of the main aspects remarked in this paper is that the evaluation of the effective sustainability and durability of a project is possible only under the appropriate values of β (considered as the main communication parameter between plant and reservoir) and of the plant size itself. This approach can be easily extended to thermal uses and medium size power plants.

As it has been previously discussed for the geothermal potential assessment, also for the reinjection strategy a general approach can't be defined for every kind of geothermal field. However general validity targets can be individuated, with the main task of maximum sustainability and useful lifetime of the plant. The mutual siting of the production and reinjection wells is often the result of a tough decision process. Numerical simulation of the reservoir circulation system is surely a useful instrument in this operation. The reinjection strategy has the role of keeping the design nominal conditions of extraction to be met for a long lifetime period. Off-design operation of such plants can be very penalizing for the efficiencies and fluid rate consumption (reservoir impoverishment).

Each coupling between a utilization plant and a particular geothermal resource would have a single optimized thermodynamic cycle and ΔT. The coupling itself is going to be considered an optimization parameter, this means that β is not given as a prescribed value. Through a numerical model, which output is the evolution and consequent response of the reservoir under a certain exploitation condition, it would be possible to globally implement this methodology. The optimization of the global "geothermal system", above described, is the synthesis of this approach. Numerical simulations can be run for forecast of future utilization or to reproduce past histories of field utilization. In forecast mode, the specific enthalpy of the geofluid extracted vs. time can be related to a model of the plant power output. Efficiency and energy production can then be estimated from this simulated parameters. A constraint to the off-design condition can be considered, for example to a minimum acceptable percentage of the nominal power output (80 % of W_{net}) to guarantee a fixed lifetime (30 years) of the plant as a possible target.

In the case of fixed design power output an increasing fluid rate should be withdrawn, if $T^* < T_{geo}$ drops, causing a decrease of the lifetime and resource durability. Connecting the numerical simulation results (temperature distribution and fluid circulation) to the plant parameters, if the working configuration is requested to be close to the nominal condition, the profiles of specific enthalpy of the geofluid extracted and power output (vs. time) should be similar.

It is evident that the elaboration of a reliable numerical model of the reservoir has a great importance for the sustainability of a geothermal project. The objective of this study is to propose a methodology for the design of a binary plant using a quite low source temperature. The methodology, of general validity, has been applied to the case of a particular area in Southern Tuscany (near Monterotondo Marittimo, Grosseto, Italy), where a geothermal resource has been estimated to be available at 400-500 m below the ground level. The study on this field is still ongoing, by other researchers collaborating with the authors, and a detailed description will be object of a further paper. Let us define the resource by the following data (qualitatively): $T_{geo} = 110 - 120$ °C; $p = 15$ bar and $T_{rej} = 70$ °C. A condensation temperature range $T_{cond} = 30 - 35$ °C is considered. The design of the plant is carried out considering the values of β used in some existing small size plants, in geothermal areas with similar resources (Table 3).

Table 3. Plants tested for adaptation at the geothermal field under analysis

	η_I %	η_{II} %	β kg/kJ	W kW	T_{sat} °C	T_{cond} °C	T_{geo} °C	T_{rej} °C
Bad Blumau (Aus)	1,89	24,57	0,1171	250	86,5	30	110	86
Wineagle (USA)	2,41	24,66	0,0899	300	66	30	110	70
Neustadt (Ger)	1,26	15,12	0,1916	230	80	30	98	78
Simbach (Ger)	0,96	15,11	0,3125	200	65,8	30	78	65

3.1. Numerical simulation of the geothermal reservoir

The models of the geothermal reservoirs are of unquestionably importance even if some limitations and criticalities are well known [3], [5] and [16]. The results reliability strongly depends from the accuracy level of the input data (thermophysical parameters, initial conditions and boundary conditions). Usually these data are known with different precision during the steps of the geothermal project, so a hard work of refinement is necessary to adapt the model to the progressive work of exploration. A schematic workflow for the realization of a numerical model is provided in Fig. 6. Calibration is an important step for the model definition. The possibility of "inverse modeling" approach is well known. It could be important to start with simple models (also lumped parameter models) to clarify the conceptual scheme and the physical consistence of the problem.

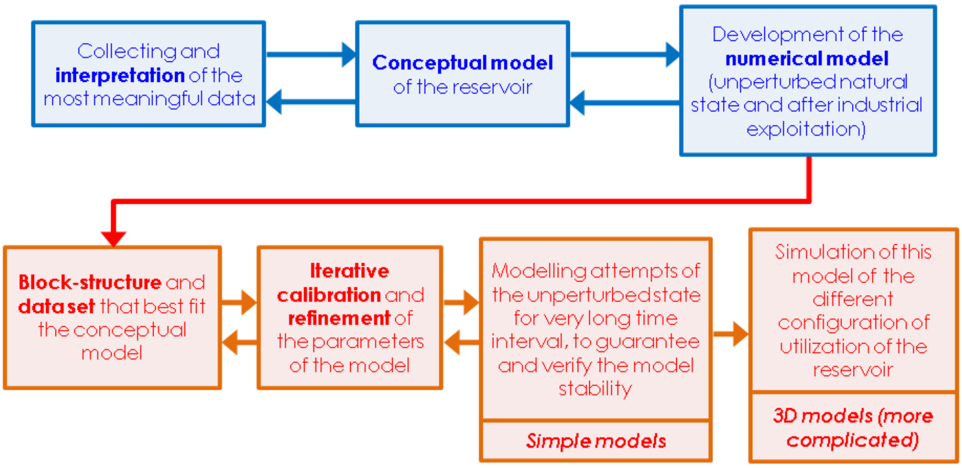


Fig. 6. Conceptual workflow for the realization of a numerical model of a geothermal reservoir

The importance of fields like the one considered is remarkable. In Italy (and generally in the proximities of the main high enthalpy fields) this kind of medium temperature reservoir are going to be exploited in the next few years by a lot of industrial subjects. A numerical model of the Monterotondo Marittimo area of Larderello field (Italy) has been realized using the commercial software Petrasim (in which is implemented the TOUGH2 simulator), [17]. The model domain extension and the various materials used are shown in Fig. 7. The conceptual model of the field is not an aim of this paper, its development is still ongoing in collaboration with other researchers. It will be covered by a further paper the authors are involved in. The model presented can be considered to be a good qualitative representation of the reservoir, and it is here used to elaborate and underline some specific features of the sustainable design methodology of an ORC power plant. Sensitivity analysis and extension of the scale of the domain are future developments of this model.

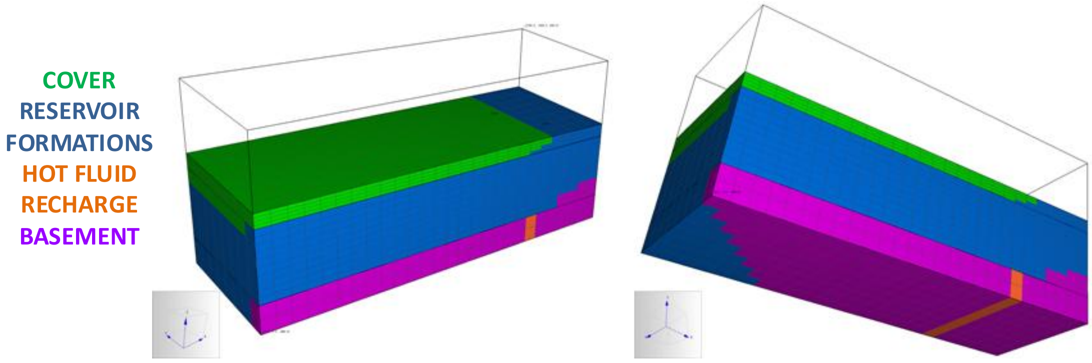


Fig. 7. Model domain and sketch of the main structural features of a numerical model grid of a geothermal reservoir

The model has been built in order to elaborate the optimal production/reinjection strategy for an ORC installation. Simulations of the natural steady-state (unperturbed) conditions of the field have been firstly run and then different exploitation scenarios have been simulated.

3.1.1. Simulation of the exploitation scenarios (ORC power plant)

The study of the particular geological structures and other exploration features will be objects of a different paper in which the authors are involved. Production scenarios have been realized to study the reservoir response to exploitation conditions and to design a possible industrial utilization of the field. The exploitation scenarios simulated are relative to production/reinjection of fluid in case of the presence of an ORC power plant with the following characteristics:

- size of the plant: 200 - 1000 kW (mass flow rate 15 - 100 kg/s)
- reinjection temperature fixed at 70 °C

Model results will be now discussed, linked to the β values and geothermal fluid mass flow rates extraction/reinjection corresponding to relative extraction temperature decrease with time and fixed power output. The value of 15 kg/s the mass flow rate is an average value for the operation of a plant like those described in Table 3, for a plant size of about 200 kW. With this low value of mass flow rate a complete sustainability of the plant is possible, because temperature reductions of 2 °C in 30 years and of about 4 °C in 50 years (Fig. 8).

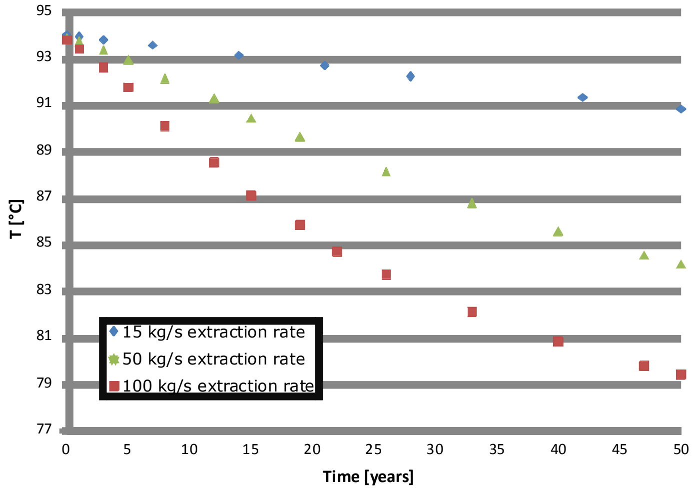


Fig. 8. Simulation of the production scenarios: temperatures at the production well (extraction/reinjection mass flow rates: 15 kg/s, 50 kg/s and 100 kg/s).

A mass flow rate extraction of 50 kg/s (for a power production of about 500 kW) determines a temperature decrease of the source of about 6 °C in 30 years and about 10 °C in 50 years, this would be critical for the plant so a sufficient life of the plant is not assured. Besides the extraction of a mass flow rate of 100 kg/s (that would permit a power output of about 1 MW) could appear to be unsustainable for this geothermal field. The diagram of temperature reduction during the lifetime of the plant is provided in Fig. 8.

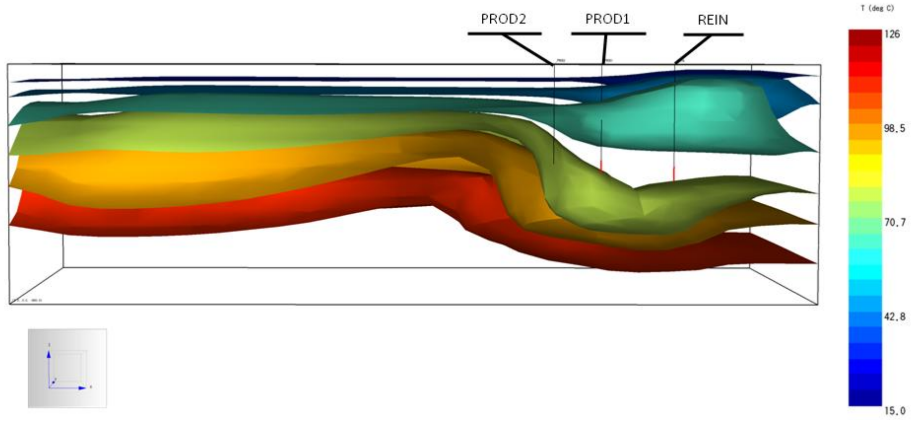


Fig. 9. Temperature iso-surfaces in the scenario with two production wells and one reinjection well.

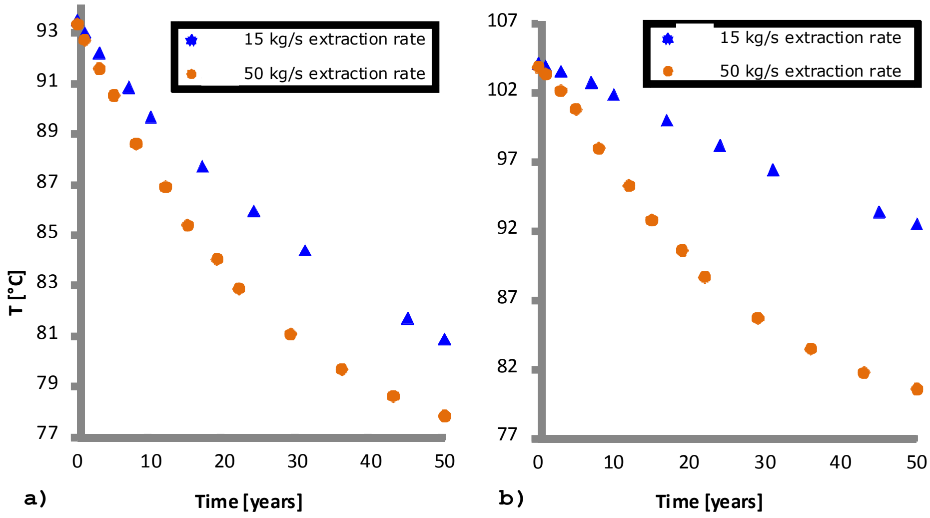


Fig. 10. Temperature evolution for the "PROD1" well (a) and for the "PROD2" well (b).

It is possible to observe temperature decreases of about 11 °C after 30 years of exploitation and 15 °C in 50 years. In both the last two cases it would be difficult to maintain a correct working of the ORC plant. A further layout scenario in which two production wells can be considered ("PROD1" and "PROD2", in Fig. 10) and one reinjection well (where the sum of the extracted flow rates is reinjected). In Figs. 9-10 the simulated extraction temperatures evolution is shown (for a period up to 50 years). For both the production wells the extraction rate of 50 kg/s is unsustainable.

4. Discussion and conclusions

The success of the application of the binary plants depends on a correct design strategy. Their efficiencies are extremely sensitive to external parameters (available ΔT of fluid, environment temperature, fluid pressure, permeability) changes. The characterization of the resource available is a fundamental initial step of each design process and it appears to be more important than the optimization of the plant itself (combination of working fluid and thermodynamic cycle).

Sustainable geothermal power production refers to the optimal extraction/reinjection fluid rate which should be maintained for a very long time, according to certain design parameters of the plant and of the wells system. This task requires an approach that join plant engineering and reservoir engineering in order to avoid overexploitation and pursuing energy-efficient utilization. Careful monitoring and exploration are essential for sustainable reservoir management. The case study here considered has a general validity value and can be extended to more complex situations, although the model has to be considered as qualitative. Numerical simulation of geothermal reservoirs is a very useful and strategic instrument to elaborate exploitation scenarios and to define a correct reinjection strategy mainly in case of moderate temperature of the source. Its reliability strongly depends on the accuracy of the input data.

The analysis has been developed with a multidisciplinary approach to geothermal systems exploitation considering the interconnections between Geoscience and Energy Engineering, concerning in particular the geothermal energy assessment. The design of a small size geothermal plant has been carried out for the exploitation of a geothermal resource in the Larderello (Italy) geothermal area (Monterotondo Marittimo). A moderate temperature geothermal source (110-120 °C), estimated to be available at relatively low depth (400-500 m below the ground level) has been considered. The adaptability of plants size of about 200 kW or discrete multiples (up to 200 kW x 5 = 1 MW) is analyzed with the support of a numerical model of the reservoir in order to elaborate a production/reinjection strategy. According to the qualitative model elaborated, a plant size of 200 kW could be run sustainably for a period of almost 30 years; the geofluid rate is estimated to be not higher than 20 kg/s. Higher fluid rates (for example twice the previous size) would be critical for the resource durability. The extraction of a mass flow rate of 100 kg/s, that would permit a power production of the order of magnitude of 1 MW, appears to be unsustainable.

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Nomenclature

c	specific heat at constant pressure, J/(kg K)
e	specific exergy, J/kg
h	specific enthalpy, J/kg
p	pressure, bar
m	mass flow rate of the working fluid, kg/s
M	mass flow rate of the geothermal fluid, kg/s
Q	heat flow rate, W
T	temperature, °C
T_o	reference temperature, K
W	power. W
v	specific volume, m^3/kg

Greek symbols

β	specific brine consumption, kg/MJ
ε	specific thermal capacity of the reservoir, kJ/kg K
ΔT	temperature difference, °C
η	efficiency
η_I	First Law efficiency
η_{II}	Second Law efficiency
Π	function of the whole “geothermal system”

Subscripts and superscripts

cond	at the condenser
CS	of the cooling system
geo	of the geothermal brine

gross	gross power
liq	of the saturated liquid
net	net value (of the power)
pump	of the pump
rej	rejection
sat	saturation
w-fluid	of the working (organic) fluid
*	value of mass flow rate, temperature and enthalpy of the reservoirs after exploitation

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