A thermoeconomic approach to the analysis of geothermal plants

Maurizio Vaccaro[1,2], Alessandro Franco[1,2]

[1] University of Pisa - Dipartimento di Ingegneria dell'Energia, dei Sistemi, del Territorio e delle Costruzioni (DESTEC, Department of Energy, Systems, Land and Construction Engineering)

[2] Unione Geotermica Italiana (UGI)

largo Lucio Lazzarino 1, 56122, Pisa (PI), Italy

mauriziovaccaro@hotmail.it

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ABSTRACT

Nowadays geothermal plants constitute a marginal part of the worldwide energy mix. In the electricity worldwide production only 11 GW on a total of about 5000 GW are geothermal plants. However a growing interest from industry and national institutions has been observed in the last ten years. The goals of sustainability and maximization of the resource durability can be pursued only through a multidisciplinary approach. Different backgrounds are involved in these studies (Energy Engineering, Reservoir Engineering, Geology and Geophysics).

The quite high economic cost of geothermal energy is well known and it is due to the exploration costs, to the drilling and plant facilities, to the variation of the resource characteristics during time and to the difficulties in obtaining "economies of scale". This last aspect is directly linked to the concept of renewability and sustainable use of the energy resources, that has been already discussed by the authors in recent papers (Franco and Vaccaro 2012). In the meantime the typical approach to the geothermal potential assessment has always been quite conservative from the point of view of technological optimization, so that a lot of installed plants have very low efficiencies. This is particularly true in the case of medium to low enthalpy reservoirs. Moreover the efficiency of small size power plants is strongly conditioned by the temperature of reservoir and environment. Reservoir temperature decline is also a complex function of the exploitation strategy adopted. Reservoir and power plant should be then considered as a global "geothermal system" together with the environment and with the energy/mass transfers between them.

On the other hand the real advantage of geothermal energy is the null cost of the energy source. During the history of the development of geothermal industry this last aspect lead to the consideration of the geothermal energy utilization only under an economic perspective. But an exclusively economic approach is not always good. The resource durability cannot always be subordinated to the economic scale (mainly for medium-low temperature resources). In this particular context the authors propose a thermoeconomic approach for the analysis of geothermal power plants. Irreversibilities and hidden costs for the reservoir restoration should be taken into account for a complete perspective of this growing industry. Different case studies are considered and discussed. The results of a thermoeconomic analysis appear to be interesting particularly in case of small size plants.

1. INTRODUCTION

The sustainability of a geothermal project involves environmental, technological and social/economic issues. An "integrated" approach in geothermal energy projects is not always implemented, particularly during the resource assessment step. Different backgrounds are involved in the feasibility and sustainability analysis and in the design of a geothermal power plant: Reservoir engineering, Thermodynamics, Earth Sciences and Geochemistry. If one of them tends to be prevalent (as it usually happens) problems may occur in the project, due to important aspects being disregarded. Social acceptance issues (for example) are often neglected during the preliminary step.

It is well known that geothermal energy suffers of high installation costs, this aspect represents a great problem for possible further development (Sanyal 2004, Stefansson 2002). This aspect is strictly connected with the lacking standardization in ORC geothermal plants technology (Franco and Vaccaro 2012) and to quite high drilling costs (Shevenell 2012). Purely economic evaluations can often affect the design parameters (particularly in case of medium-small size geothermal power plants, mainly ORCs) with the tendency to overestimate the plant size, then operating with low efficiency (or low resource durability). These plants have different characteristics with respect to the more traditional geothermal ones, using geothermal resources with a moderate enthalpy content (Franco and Villani 2009).

Binary cycle power plants are object of a growing interest in the renewable energy market (also in Italy). Anyway their diffusion is strongly dependent on the geographical distribution of the geothermal resources. The efficiencies are usually low and strongly conditioned by external parameters changes (Franco and Vaccaro 2012). A size optimization process is necessary, in order to reach an appropriate compromise between profit and sustainable utilization of the resource. Under a general perspective it is interesting to use the Thermoeconomic analysis for the feasibility assessment of a geothermal plant, depending on the type of plant considered and of the resource available. The thermoeconomic analysis of energy systems is an useful instrument of synthesis between Thermodynamic optimization and Economic optimization. The applications of this approach are well known in the literature (Bejan et al. 1996, Lazzaretto and Tsatsaronis 2006), but only marginal applications are devoted to geothermal plants (Arslan 2010).

After a brief discussion about the available methods present in the literature, the particular thermoeconomic approach developed by Franco and Giannini (2004 and 2005) is here taken into account as a synthetic method for a sustainable and optimal design of a geothermal plant, considering Thermodynamics (efficiency increase), Economics (reduction of specific costs with size increase) and Reservoir Engineering elements (sustainable extraction rate, reinjection strategy). The particular tool is applied with reference to existing plants and the results are discussed. The optimization strategy is supported by the instrument of numerical simulation of reservoirs, that represents a key element for the optimization and the sustainability assessment.

2. THE SUSTAINABLE DESIGN OF GEOTHERMAL PLANTS

The great part of geothermal resources available around the world are water dominated fields, at temperatures under 150 °C and pressures below 15 bar (Stefansson 2005). The binary cycle technology using Organic Rankine Cycle (ORC) represents a promising solution for power production from these fields. Some manufacturers (Pratt & Whitney/UTC, Siemens) have proposed small size (about 0.2 MW) standard power machinery systems. Standardization 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 about renewable energy sources. The successful productivity and the maximization of the plant lifetime only depend on the resource characteristics. 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 (in terms of mass and energy transfers).

The key factors governing the optimization of a plant are mainly mass flow rate extraction (potential assessment) and the reinjection strategy, considering the scaling phenomena (Axelsson, 2010). Typical problems due to an incorrect characterization of the available resource can be:

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

These problems are well known and they have been largely discussed by the authors of the present paper (Vaccaro et al. 2011, Franco and Vaccaro 2012) but they are unfortunately little considered in the energy industry. Major decisions about energy conversion systems design are based today on the economic paradigm (although mathematically sophisticated and internally consistent) which is not sufficiently compatible with the laws of Thermodynamics (particularly the Second Law). Contemporary economic analysis pays only marginal attention to the availability and the durability of the geothermal source. This aspect represents a serious conceptual drawback to the possibility of a real development of medium to low enthalpy geothermal industry, as shown by some interesting case histories (Porras and Bjornsson 2010) and the recent developments of ORC industry. The exploitation of geothermal sources is often attractive on a general point of view, but some primary operative parameters (e.g. plant size, extraction rate) can affect the economic scenario (profitability), not encouraging the real development of the plants. This approach is typical when the resource is not well characterized, or the investment planning are made only thinking to the economic paradigm and scenario, rather than to the available resource.

ORCs efficiencies decline with the worsening of external parameters, this aspect emphasizes the lacking process here described. This has apparently occurred in Italy in the last five years, where, notwithstanding the growing interest in the field, no plants have been built or developed yet. On the other hand the external scenario is not steady, but continuously in progress. Boundary conditions change in terms of resources (price of fossil-fuel supplies) and economic scenario (market liberalization).

3. GEOTHERMAL ENERGY COSTS: A BRIEF SURVEY

The evaluation of the specific cost of geothermal energy is a very difficult task, particularly for the case of interest of the present paper: utilization of medium-low temperature geothermal resources. The data are not always available mainly for what concerns the source (e.g. drilling costs, reservoir maintenance costs) and the components (a massive production of components is not pursued, and all the plants represent a specific case). All the factors affecting the specific cost of geothermal energy conversion are analyzed and linked to the technical and geological-geophysical issues (Sanyal 2004, Stefansson 2002). The cost of the electricity (C_{in}) is the sum of investment cost (C_Z), Operation and Management cost ($C_{O\&M}$), make-up wells cost (C_{MW}), plant cost (C_{pp}), and inhibitors cost (C_{inhib}):

$$C_{in} = C_Z + C_{O\&M} + C_{MW} + C_{pp} + C_{inhib} \qquad [1]$$

A preliminary cost assessment is an important part of an iterative decision making process. For example the wells productivity (deliverability) strongly affects the specific cost, and it varies with time. Different correlations (depending on the depth) can be used for the drilling costs estimation (Shevenell 2012), see Fig. 1. The plant cost (C_{pp}) is evaluated according to Bejan et al. (1996), considering a reference plant (using the same technology of the case considered) used as a comparison, according to the following equation

$$C_{pp} = C_{pp}^{*}\left(\frac{P}{P^{*}}\right)^{q} \qquad [2]$$

where C_{pp}^{*} is the annual cost of the reference plant, P^{*} is the reference power size, while q is an appropriate exponent (in the cases treated in this work it has been assumed equal to 0.6), so a review of several cases from literature can be useful in order to identify a similar plant with economic data.

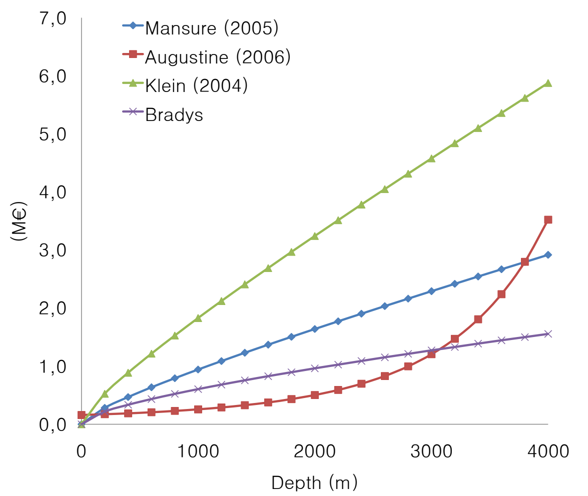

Figure 1: Drilling costs estimations through different correlations (after Shevenell 2012).

According to Stefansson (2002) the investment costs can be divided into "surface costs" and "underground costs". Surface costs are mainly referred to the power plant (energy conversion system), while the underground costs deal mainly with the drilling operations. Exploration costs, in case of medium-small plant size (5–10 MW), are usually a relatively little component, if dealing with already known fields. Anyway the exploration and plants diffusion is now focusing on unknown or not developed fields, so that the exploration costs would have more importance in the future. Investment costs and O&M specific costs can be usually estimated by an exponentially decline law of the type

$$c = l \cdot \exp\left[-m \cdot (P - n)\right] \qquad [3]$$

where c is the specific cost (investment or O&M) respect to the energy output, P is the power output of the plant, and l, m and n are appropriate coefficients (Sanyal 2004). The make-up wells (when they are needed) cost is the result of a complex function of the initial number of wells, the specific cost per well, the annual energy produced by the plant, and the decline rate of productivity of the other wells.

4. THERMOECONOMIC APPROACH TO THE PLANTS DESIGN AND ANALYSIS

The geothermal energy utilization can be considered from various points of view: technological (power, efficiency), economic (global annual cost, pay-back time), environmental (emissions), and so on. Thermoeconomic approach starts from considering Thermodynamics laws and balances. Methods based on the First Law of Thermodynamics do not usually provide detailed information about internal losses, treating all the energy fluxes as equivalent, without differentiating by different grades or values (in Fig. 2 a simplified energy balance of an energy conversion system is shown). Consequently they are not suitable for focusing on evaluation of performances and costs.

The exergy approach to energy systems analysis has been the first effort to overcome these problems. Detailed analysis based on Second Law concepts show the intrinsic limitations in the First Law techniques (Kotas 1995), helping to find the actual sources of irreversibility in processes and components (see Fig. 3). The loss of exergy, or irreversibility, provides a quantitative measure of the inefficiency of the system and it is particularly indicated for geothermal systems. Second Law analysis allows to carry out the plant optimisation (Brodyansky et al., 1994). Exergy analysis also proves to be useful as a proper measure of environmental impact.

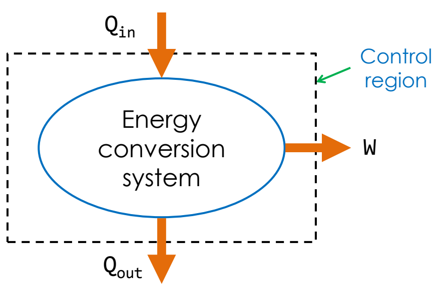

Figure 2: A simplified energy balance between an energy conversion system and environment.

The limits of exergy analysis appears if monetary costs are put together with thermodynamic aspects. This problem has been assessed in different way by

Thermoeconomic Analysis (Bejan et al. 1996). Various methodologies are based on a proper integration of Thermodynamics and Economics aspects, making possible the direct evaluation of the impact of the energy conversion in the productive structure of a system. The aim of such thermoeconomic analysis is to combine the Second Law description of the plant, the capital and initial costs and the prices of the product streams. In more general terms an analysis becomes thermoeconomic when a cost structure is associated to the exergetic flow rate of a real process, and the inefficiency causes are identified, located and quantified.

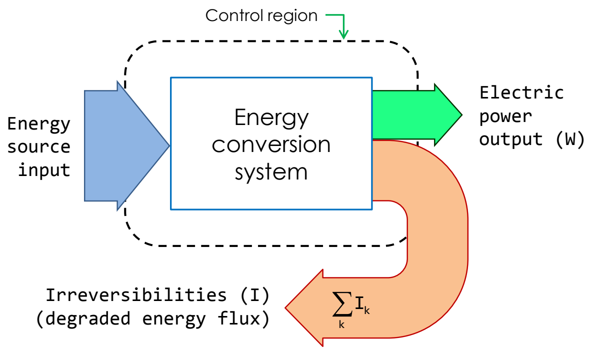

Figure 3: A simplified energy balance between an energy conversion system and environment.

An interesting approach belonging to this category consists on addressing the trade-off between thermal efficiency and capital expenditure only through the use of one quantity: the Exergoeconomic cost (Valero et al. 1999). This method seems to be suitable specially for plant analysis, even if not easily applicable in case of optimization problems. Notwithstanding the good ideas contained in the different approaches belonging to Thermoeconomics, such analyses show some intrinsic theoretical limits, and the necessity of introducing some arbitrary elements.

The thermoeconomic approach allows to consider also different thermodynamic systems and compare them (under well defined hypothesis). Here the whole system optimization is considered (in terms of resource durability and technical-economical feasibility), instead of studying each single component of the plant. According to the type of power plant, different ways of cost balance definition can be adopted. There exist both exergonomic methods and higher level (system-level) methods.

4.1 Geothermal energy systems analysis through a thermoeconomic approach

Geothermal power plants are characterized by a single energetic input (geothermal resource) and a single (or multiple) output (electricity, in the most simple configuration, or also district heating grids). One of the main tasks is to demonstrate that the power output and extraction rate are directly related to the resource sustainability assessment, and that a purely economic evaluation of the power size is wrong or counterproductive. For this reason a thermoeconomic approach is pursued, through an interdisciplinary view of the problem.

The thermoeconomic analysis carried out in the present work is based on the assumption that the total cost of the power plants is equal to the sum of the costs related to the exergy losses plus the operating (initial) costs (related to installation and operation). The thermoeconomic optimization considers as objective function the minimization of the above defined total cost of the plant. The key element is represented by the definition of the cost of the exergy losses. The exergy destruction (meaning the destruction of potentially available mechanical energy) must be then computed as a cost (maybe sensibly higher than the one of the energy source). In Fig. 4 the scheme for the system balance equations is shown (also considering fuel cost, in a general way). In the exergy balance the entering exergy stream is the only input to the system, while there are both useful power stream and irreversibilities (or missing production) as outputs. Irreversibilities cost C_I is indicated between the inputs to the cost balance, while it is an output in the exergy balance (the lost income is then calculated as a cost).

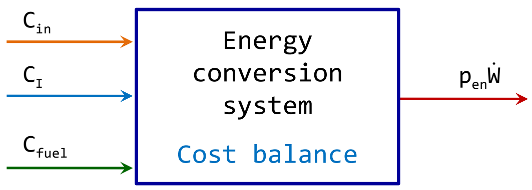

Figure 4: Exergy (above) and thermoeconomic (below) balances for an energy conversion system.

Considering renewable energy systems one can assign a null cost to the primary energy source (specific cost of the "fuel"). Anyway geothermal energy is different respect to other renewable resources (for example sun or wind energy): its renewability depends on several factors, also technological and due to the exploitation strategy. This assumption of null energy source cost (in case of geothermal energy) can also be reviewed, in order to better comprehend technical-economic feasibility and sustainability assessment.

Let us call C_I the cost of the irreversibilities, and $\dot{E}_{in} = \dot{m}_{in}\varepsilon_{in}$ the exergy stream entering into the system (being ε_{in} the specific exergy). If C_{fuel} is equal to 0, the final balance cost equation of the system is

$$C_{in} + C_I = p_{en}E_{out} \qquad [4]$$

The system is then considered suitable from a thermoeconomic point of view only if

$$C_{in} < C_{\max} = p_{en}E_{out} - C_I \qquad [5]$$

where C_{max} is the maximum sustainable (or affordable) cost. It appears to be important how the specific price is assigned to an energy output by the National or Regional energy price policies and regulations. This issue is valid also in case of thermal power output (e.g. district heating). Another important problem is the definition of the specific cost of the exergy loss c_I, several strategies can be adopted:

a) considering c_I as the cost of the fuel (this seems to be the less realistic one);
b) considering c_I as the cost of the fuel divided for the efficiency of the plant (in case of the geothermal plants one can assume about 0.2);
c) considering that exergy losses correspond to a lower energy availability, and they are associated to the cost of the "fuel" divided for the average efficiency of the installed plants (typical national grid values can be 0.35–0.40).
d) another possibility (referred to the examples treated in this paper) is to consider the exergy losses equal to an average value of the selling price of the electrical energy. This last option derives from the consideration that exergy losses cause a lower energy output and then a lower amount of energy to be sold.

4.2 "Modified" power and extraction rate

Let us introduce the "modified" power $\dot{W}^*$ and "modified" extraction rate $\dot{m}^*_{geo}$. They give an idea of the production/extraction rate according to the effective costs sustained. If $C_{in} > C_{max}$ then the "modified" power and extraction rates are referred to the effective cost sustained and give an idea of the power output to justify this value (usually higher than the real one). If $C_{in} < C_{max}$ then the system is sustainable, and the "modified" parameters are an evaluation of the equilibrium point that can be reached if enhancing and increasing the production. In any case it is not recommended to keep the system near this equilibrium point, being this a limit for the sustainable development of the "geothermal system" considered. The "modified" power and extraction rate must be referred to the larger cost value (C_{in} or C_{max}), then they can be derived by the exergy balance and from the thermoeconomic balance (illustrated above), considering also the Second Law Efficiency of the plant (η_{II}) and the time t (First Law Efficiency η_I and Second Law Efficiency η_{II} are defined according to Franco and Villani 2009):

$$\dot{m}^*_{geo} = \begin{cases} \dfrac{C_{in}}{t\varepsilon_{in}\eta_{II} - c_I(1-\eta_{II})} , & C_{in} > C_{max} \\ \dfrac{C_{max}}{t\varepsilon_{in}\eta_{II} - c_I(1-\eta_{II})} , & C_{max} > C_{in} \end{cases} \quad [6]$$

It is evident that the Eq. [6] has no meaning in case the denominator is negative, so a condition like the following has to be assigned:

$$\eta_{II} > \frac{c_I}{c_I + p_{en}} \quad [7]$$

4.3 Application of Thermoeconomic analysis to existing power plants

Some examples of application to existing plants of the simplified Thermoeconomic approach here described are given. Mainly four Turkish power plant case studies are considered (due to the amount of data from literature), a more detailed and general analysis is available in Tedesco (2013). Geothermal exploration in Turkey started in the 1960s, firstly focusing on high enthalpy reservoirs (Serpen et al. 2010).

Table 1: Main data about the case study power plants.

Plant	Power (MW)	η_I (%)	η_{II} (%)	$\dot{E}_{in}$ (MW)	h/y (h)	Energy (GWh)
Tuzla	5.2	14.06	57.7	8.96	8541	1.21
Dora 1	6.5	12.2	45.9	14.17	8462	55
Dora 2	9.8	9.3	35.8	27.35	7143	70
Kizildere	15.6	12.8	59	26.4	5751	89.6

In Table 1 the main energy production data of the four plants considered are listed. $\dot{E}_{in}$ is the entering exergy stream (from the resource). The plants layout is shown in Fig. 5 (Coskun 2011), the geofluid is firstly separated into two phases, then it transfers heat to a secondary fluid, which expands in the turbine of a binary cycle (pre-heaters are used in order to use exhaust streams exiting the evaporator and the turbine). The Kizildere instead is a combined plant, flash with bottoming binary unit (Dagdas et al. 2005).

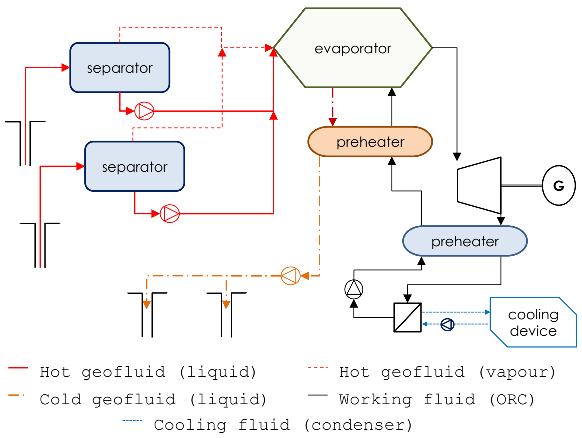

Figure 5: scheme of the Tuzla power plant, after Coskun (2011).

The Valle Secolo direct steam expansion plant (near Larderello, Pisa, Italy) is considered in this section as a comparison, being an efficient, high enthalpy power plant, with very low cost (mainly O&M) if compared with the others. The extracted steam is at about 200 °C. The power output is 103,6 MW, with η_I = 17 % and η_{II} = 62 %. The exergy losses are estimated to be 67 MW. It is obvious that it is a greater size plant, working with high reliability, and higher number of annual working hours. Here a matching is given to have an idea of the different order of magnitudes of power/energy production and costs, and to quantitatively remark the difference between the geothermal plants types. Also a binary cycle power plant is considered to be compared with the Turkish example plants, having a smaller power output: Bad Blumau (Austria) ORC plant. It produces about 180 kW (70 kW exergy losses), with η_I = 1.9 % and η_{II} = 73.5 % (Legmann 2003).

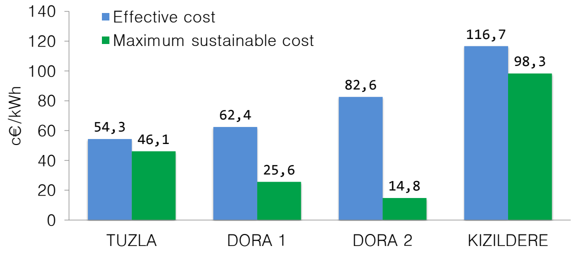

Figure 6: Thermoeconomic costs estimation for the plants considered.

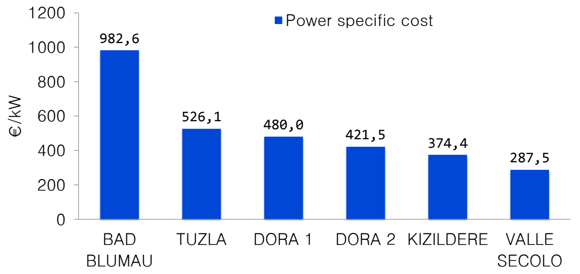

Figure 7: Power specific cost estimation for the plants considered.

An estimation of the maximum sustainable cost (C_{max}) is here carried out for the example plants. This cost is then compared to the effective cost C_{in}. The inflation and interest rate are here neglected. The well productivity is considered constant for all the time interval considered in this analysis (20 years). The specific price of energy (p_{en}) is here assumed to be 0.1 €/kWh. This estimation can be considered surely conservative, with respect to the national market policies about renewable energy resources incentive. For the irreversibilities the hypothesized specific cost is 0.065 €/kWh, being 65 % a weight referred to the exergy destruction. Having the Dora 2 power plant a very low η_{II}, a c_I equal to 0.05 €/kWh is considered. The drilling costs are considered as a part of the investment costs, they are "underground costs", according to Stefansson (2002). A comparison between the thermoeconomic costs is shown in Fig. 6. In Table 2 the cost item distribution are illustrated.

To give an idea of the differences between the kind of plants here considered, let us calculate a specific power cost (Fig. 7). It is possible to see how the small plants have high specific costs (€/kW). This is the main factor contributing to a predominant role of the purely economic paradigm in the design decision making processes. Anyway the environmental benefits or incentives are not considered in this conservative analysis.

Table 2: Thermoeconomic analysis, case studies: effective costs.

Plant	C_Z (M€)	$C_{O\&M}$ (M€)	C_{pp} (M€)	C_{inhib} (M€)	C_{in} (M€)
Tuzla	0.6	1.03	0.95	0.14	2.72
Dora1	0.75	1.27	1.09		3.11
Dora2	1.12	1.61	1.4		4.13
Kizildere	1.75	2.03	1.85	0.2	5.83
Bad Blumau	0.02	0.03	0.13		0.18
Valle Secolo	8.96	15.06	5.76		29.78

In case of small size power plants the plant cost itself tends to prevail. For the greater size plants, investment costs and O&M cost are higher. Also through this approach it is evident how the technical and economic sustainability of a geothermal plant strictly depends on the type of resource and power output. Cases like the one of Valle Secolo are usually associated to reservoirs with great extension, which allow a huge extraction rate (at a higher enthalpy content of the fluid). In case of moderate temperature fields (particularly new exploration fields, like the one which are now considered interesting by the market and policy institutions) huge extraction rates can lead to unsustainability and fast resource depletion. The not good performances Dora 2 power plant are evident if considering also "modified" power and extraction rate values. About 5.5 times (1304 kg/s and 55.3 MW) the actual extraction rate (244 kg/s) and power size (9.8 MW) would be necessary to make this plant sustainable, according to the conservative hypothesis about market and economic context here considered. The modified extraction rate according to this analysis is surely unsustainable from an environmental point of view. In the case of Tuzla $\dot{m}^*_{geo}$ would be only 122 kg/s, respect to the current 103 kg/s.

5 A THERMOECONOMIC APPROACH FOR PLANT SIZING

Thermoeconomic approach and resource characterization through numerical simulation is the key factor of these analysis. A possible workflow for the sizing and sustainability assessment of a geothermal power plant is shown in Fig. 8. It is here proposed to consider the thermoeconomic assessment as a first step to define a plant size (and geofluid rate), to be then evaluated with different tools. $\dot{W}^{(I)}$ (in Fig. 8) is the first attempt output value, as an input of the iterative process. It is evident the important role which is here assigned to the numerical simulation of the reservoir, as to other reservoir engineering aspects (wells siting, fluid losses, tracer test). Only at the end of this interdisciplinary and integrated evaluation a sustainability assessment can be accomplished.

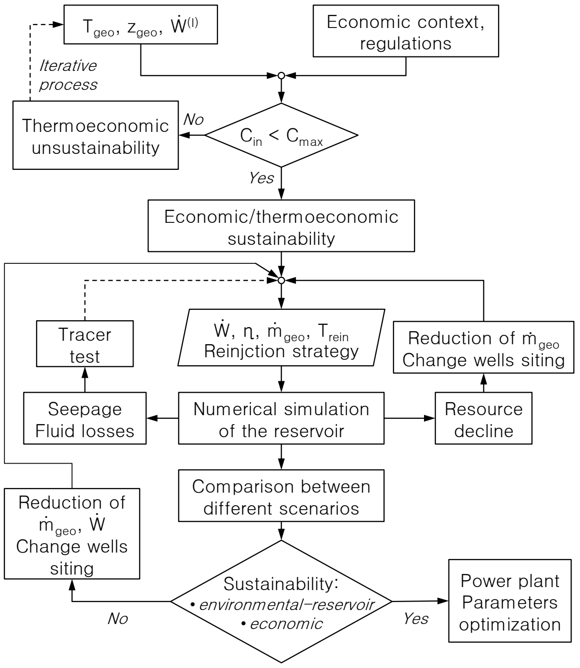

Figure 8: Possible workflow proposed for the integrated approach.

It is valid only in case of medium-low temperature geothermal resources. High enthalpy fluid utilization plants have different problems, and in general their productivity is less dependent on external parameters variations. One important element of this sketch is that the power output of the plant (and consequently the extraction/reinjection rate) is not an independent variable, but it derives from an iterative process. The inputs to the design and optimization can be then calculated after the simulation of different exploitation scenarios. Numerical simulation of geothermal reservoirs can be here a good instrument for the evaluation of the production scenarios (O'Sullivan et al. 2001, Antics 2001, Cacace et al. 2010), previously identified through the thermoeconomic approach.

6. CASE STUDY ANALYSIS

6.1 Momotombo (Nicaragua)

The case study of Momotombo geothermal area is here considered. Production history data are derived from Porras and Bjornsson (2010). Different plant units have been used to exploit the resource: two flash units (total 70 MW) and then a binary cycle unit (7.5 MW). The missing energy production (respect to the nominal power size) is here considered as a missing income, and a cost is assigned to this gaps (the same value of the selling energy price here hypothesized). A "cost" of 0.05 €/kWh is associated to the missing production (irreversibilities or missing output for different unknown reasons). The price of energy is also here assumed 0.1 €/kWh, considering 8000 working hours per year. The operative costs are then higher when the production is far from the nominal level (of the year considered). The extraction-reinjection rates (from historical data) are shown in Fig. 9.

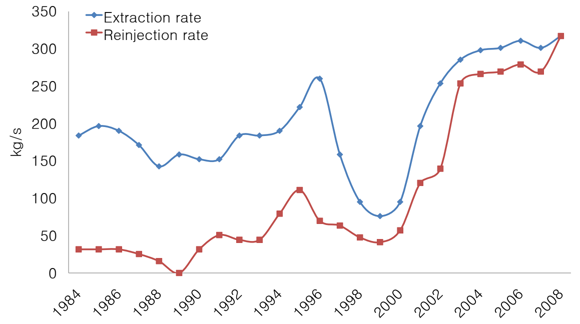

Figure 9: Extraction and reinjection rates, historical data (Momotombo).

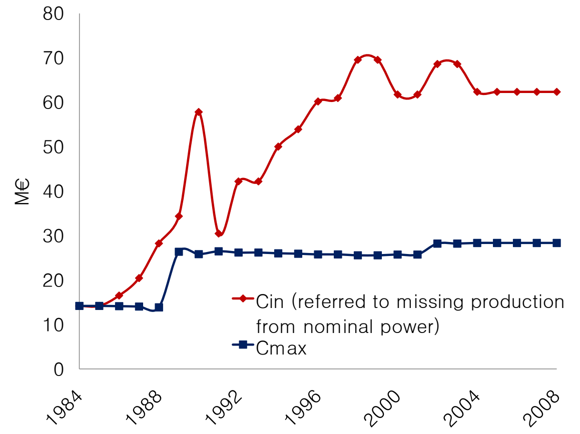

Figure 10: Comparison between C_{max} and C_{in} referred to the missing production respect to the nominal power (Momotombo).

Some very conservative hypothesis about the market energy price are assumed in the case studies considered in this work. Twenty years is the interval considered to distribute the investment over, and a specific inhibitors cost is also considered (by a general literature estimation). A severe point of view is taken into account, assigning also a "cost" to the gap between nominal and effective power output (Fig. 10). The modified power is also calculated and it is shown in Fig. 11.

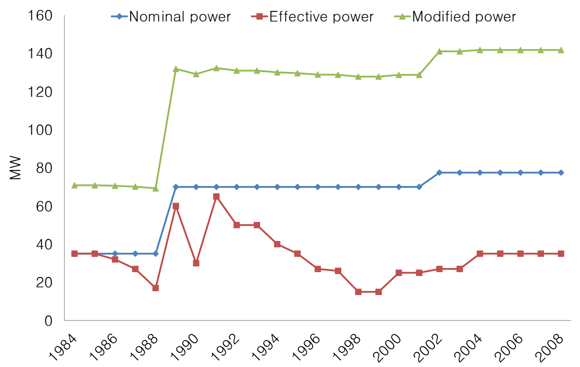

Figure 11: Comparison between nominal, effective and "modified" power trends with time (Momotombo).

As it can be seen from Fig. 10, the C_{max} is always smaller than the effective annual costs, giving a substantial thermoeconomic unsustainability. In the case of Momotombo the modified power estimation gives very tough response about the performances of this power plants group (Fig. 11). $\dot{W}^*$ reaches more than 140 MW. This element has to be linked also to periods of low productivity (~10 MW), without reinjection, but with a nominal power installed of 70 MW. Resource depletion lead certainly to a lack of productivity (decline of energy production, growth of costs), also for a scarse characterization of the field and reservoir behaviour.

6.2 Miravalles (Costa Rica)

Miravalles geothermal production is here introduced to evidence a case study in which thermoeconomic sustainability is achieved. A 55 MW unit was first run in 1994, since then 53 wells have been drilled, with depths in the range between 900 m and 3000 m (production, reinjection and exploration wells). The reservoir is water dominated, with an average geofluid temperature of 240 °C (Moya and Nietzen 2010). The data about the plants and the reservoir at Miravalles are available in DiPippo (2008) and Moya and DiPippo (2007), see Table 3. A historical scenario is considered and then a more severe scenario (deriving from the calculation of the modified power) is considered and discussed. In the Miravalles case study the nominal power is assumed to be equal to the annual value of the net power.

Table 3: Miravalles case study: annual power and energy output, extraction rate and efficiencies.

Year	Power (MW)	Hours/ year (h)	Annual energy (GWh)	$\dot{m}_{geo}$ (kg/s)	η_I (%)	η_{II} (%)
1994	52	6648	345.7	760	7.2	27.7
1995	57	8211	468	780	7.7	29.6
1996	62	8219	509.6	800	8.1	31.4
1997	67	8124	544.3	820	8.6	33.1
1998	119	4973	591.8	1526	8.2	31.6
1999	114	7051	803.8	1506	8	30.7
2000	136.5	7164	977.9	1906	7.5	29
2001	136.5	7229	986.7	1906	7.5	29
2002	136.5	8210	1120.7	1906	7.5	29
2003	136.5	8380	1143.9	1906	7.5	29
2004	152	7930	1205.3	1906	8.4	32.3
2005	152	7559	1149	1906	8.4	32.3
2006	152	7566	1150	1906	8.4	32.3

Inhibition and neutralization systems against scaling phenomena have been used at Miravalles (Sánchez-Rivera et al. 2010, Moya and Nietzen 2010), in order to enhance the productivity and avoid the typical problems due to scaling phenomena (Corsi 1986). According to Moya and Nietzen (2010), both a inhibition systems and acid neutralization systems are used. A very interesting evaluation (both in terms of delivered energy and costs) has been made by Sánchez-Rivera et al. (2010) and Moya and Nietzen (2010), to individuate the advantage of having an inhibition system. The lack of inhibition system would lead to an undelivered annual energy of about 12.8 GWh (61.3 GWh would be be the annual production using inhibition). The inhibition system total cost has been estimated to be about 1.53 M$ (in 2010), with an annual cost of about 0.2 M$ (2010) per year.

It is evident from Fig. 12 (in which the annual trends of C_{in} and C_{max} are shown) that the Miravalles geothermal production is sustainable according to the thermoeconomic approach here considered, as C_{in} is kept always smaller than C_{max}. One reason is surely linked to the inhibition systems (used since the beginning of the production), which help to reach a higher productivity rate respect to a scenario without any inhibition or acid neutralization.

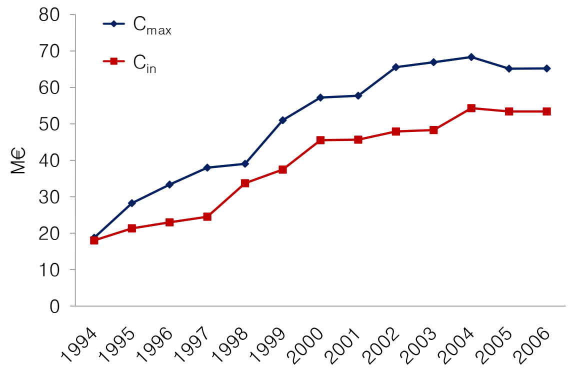

Figure 12: Annual trend of maximum sustainable costs and effective costs (Miravalles).

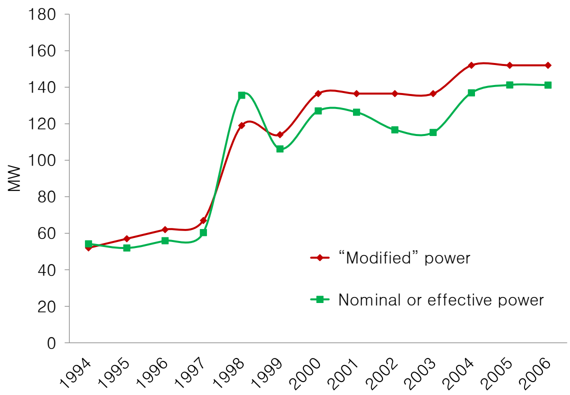

Figure 13: "Modified" power and nominal power trends (Miravalles).

As for the case study of Momotombo also for the Miravalles geothermal production the "modified" power can be evaluated (Fig. 13). In this case the effective costs are always less than the maximum sustainable (or affordable) costs, then it would be possible to have a "modified" power smaller than the effective one.

It could be interesting to evaluate the possibility of reaching higher extraction rates. This could be done by implementing a numerical model to understand the reservoir behaviour under a more severe extraction rate. The point is to determine how far from the current equilibrium point the production can be brought without disturbing too much the geothermal system. In other words, the simulation of this reservoir would be a way to investigate about the enhancement of the productivity of the power units.

7. CURRENT DEVELOPMENT OF SMALL SIZE PLANTS INDUSTRY IN ITALY

The development of geothermal binary cycle power plants appears to be one of the aims of different countries worldwide. New players are now interested in the development of this technology. In Italy the geothermal resource utilization for electricity production has a long history (Cataldi and Ciardi 2005). The market of geothermal power plants has been controlled since tens of years from one single player (ENEL). The liberalization of the energy market started in 1999. Only recently the market of geothermal power production has also been liberalized (2010). In Italy, at the present time, about 43 applications for geothermal exploration are active according to the Ministry for Economic Development website, almost all in Latium (25), Tuscany (7), Sardinia (7), Sicily (4), Umbria (4), and Lombardy (1). 43 geothermal exploration concessions have been granted, mainly in Tuscany (33), Latium (9), Sicily (1), and Lombardy (1). 9 "experimental plants" instances of permission are in progress, and 13 are the received applications by the Ministry of Economic Development (some applications are counted twice because they are referred to more than one Region).

These aspects could determine a meaningful expansion of geothermal power plants market in Italy, anyway, by outside the industry, it could appear that both players and legislation are not up-to-date about technology and sustainability assessment of medium-low temperature geothermal projects. Particularly for small size ORC plants, technical-economical and environmental sustainability are not ensured only thanks to the small plant size. The characterization of the resource together with an exploitation strategy based on a numerical simulation of the system (plant-reservoir) can be seen as key factors of this assessment. Evaluation tools like exergoenvironmental analysis are not implemented in market or institutional backgrounds yet. A purely economic approach to the industry and market evolution of these systems is not successful. A wider perspective approach is needed, to consider the evolution of the plant-reservoir system behaviour and economic sustainability.

8. CONCLUSIONS

The necessity of an "integrated" approach to the study of geothermal reservoirs utilization is shown. A purely economic approach is considered to be counter-productive. Some possible applications of a Thermoeconomic analysis tool to geothermal energy utilization are illustrated. This tool can be useful both for a preliminary feasibility analysis of the plant (e.g. definition of an appropriate size of the plant), and for an optimization of the main operating parameters.

A review of the cost items of geothermal power plants (according to the current literature assessments), for the definition of the economic structure of Thermoeconomic analysis is presented. The application of the methodology has been described with reference to some existing geothermal power plants. Momotombo (Nicaragua) and Miravalles (Costa Rica) cases are considered in this work in order to illustrate the thermoeconomic analysis features (only one case can be considered thermoeconomically sustainable). A methodological proposal for the design and sustainability assessment of geothermal projects has been elaborated, trying to contribute to a more sustainable approach to the plants design. The geothermal plants market is considered and some observations are made about its development according to a thermoeconomic perspective.

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