European Geothermal Congress 2016
Strasbourg, France, 19-24 Sept 2016

A matrix method to select the more suitable extraction technology for the Campi Flegrei geothermal area (Italy)

Claudio Alimonti[1], Elena Soldo[1], Davide Berardi[1], Donato Bocchetti[1]

[1] La Sapienza, University of Rome, Via Eudossiana 18 – 00184 Roma

claudio.alimonti@uniroma1.it

Keywords: wellbore heat exchanger, geothermal energy, energy conversion plant, ORC, matrix, binary power plant, Campi Flegrei.

ABSTRACT

This paper presents a Selection Matrix to compare the binary power plant technology proposed in the area of Campi Flegrei (Italy) to a deep borehole heat exchanger power plant.

The Selection Matrix is composed of several indices with weight for the calculation of the final score of the project. The aim of the work is to provide an evaluation instrument of two different geothermal power plants, as well as to highlight that the results of the evaluation depends on the weight the decision maker assigns to the indices, considering the specific features of the territory where the plant is located.

1. INTRODUCTION

Italy is the first country in the world to use geothermal energy to produce electricity from the power plant located in Larderello (Tuscany), which remains the fifth biggest geothermal power plant in size, having an installed power of 862.5 MWe (Di Pippo, 2012). Contrary to what happened in Tuscany, the geothermal resources in the underground of Campania region are only used for thermal and touristic purposes, not for heat nor electricity production.

A pilot project for a binary power plant in the area of Mofete (Campi Flegrei) has been proposed to the Economic Development Ministry. During the last years, all the projects in Italy which entail underground operations get frequently a negative social response, due to concerns of the population regarding seismicity of the national territory and the possible contamination of the groundwater. The projects of geothermal power plants in the Campania region fall into this category.

Based on the Villafortuna Trecate case study (Soldo & Alimonti, 2015), this paper introduces an updated version of the Selection Matrix to compare two different utilization technologies of the geothermal energy of Campi Flegrei: a binary power plant and a heat exchanger installed in the well.

The Selection Matrix is composed of several indices with weight for the calculation of the final score of the project. The indices can be classified into three macro areas: the technical and engineering indices, the social and environmental indices and the economic index. The work presents the final result, depending on the assigned weight on the macro areas, considering the specific features of the territory where the plant is located.

2. CAMPI FLEGREI AREA

The Campi Flegrei area has a typical horseshoe shape and is located in the north-west limit of the Napoli gulf; the area is a caldera of 12 km with the centre in the Pozzuoli bay. The site of the pilot project is the Cuma research area, located in the western part of Campi Flegrei, in the area of Mofete (Fig. 1).

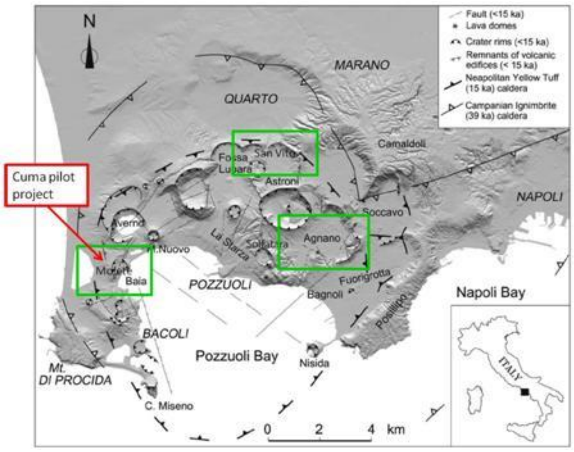

Figure 1: Campi Flegrei caldera (modified picture from Costa et al. 2009).

The most interesting areas from the geothermal production point of view are Mofete, San Vito and Agnano, which are indicated in Fig. 1. Regarding the Mofete area, three aquifers have been identified. The first aquifer is between 500 and 1000 meters with 20% of vapour and temperatures in the range 100 ÷ 130 °C; the second aquifer is at a depth between 1800 and 2000 meters (40% of vapour and a medium temperature of 300 °C); the deepest aquifer level is between 2500 and 2700 meters and it is probably a vapour dominated system. The medium geothermal gradient of the Mofete area is almost 180 °C/km.

The Cuma pilot plant will be developed in the district of Bacoli, an area characterized by an high urbanization. The Cuma field, including the geothermal power plant, the wells and the transport pipes, has a size of almost 21000 m^2.

3. TWO DIFFERENT GEOTHERMAL PROJECT PLANTS

Two different geothermal plants will be compared: the Cuma binary power plant and a heat exchanger installed in the well, the WellBore Heat eXchanger (WBHX) according to the acronym of Nalla et al. (2005).

3.1 The closed loop binary power plant

Closed loop binary power plants (Fig. 2) are composed of the production wells, the ORC unit and the reinjection wells. The geothermal water and the working fluid of the ORC circulate in separated loops and never come in contact with each other (Hettiarachchi et al., 2007). Therefore, binary power plants have minimal environmental impacts: the loop is closed and no leakage of brines can occur into the subsurface; the only occurring emission is water vapor in case of water cooling towers. The reinjection of the brines avoids the depletion of the reservoir and reduces the risk of land subsidence.

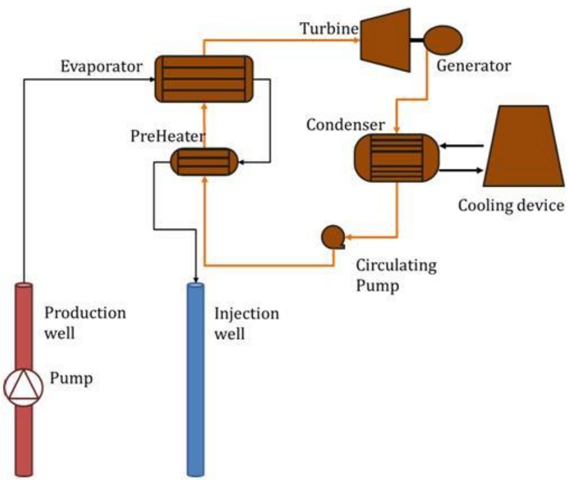

Figure 2: Typical scheme of a closed loop binary power plant.

In Table 1 all principal characteristics of the CUMA pilot project plant are listed.

Table 1: CUMA pilot plant.

Type of plant	Binary power plant (ORC unit)
Size of plant	5 MWe
Number of production wells	3
Number of injection wells	2
Depth of wells	900 m
Flow rate	168.33 m^3/h
Wellhead temperature	180 °C
Reinjection temperature	85 °C
Thermal power per well	18.2 MW
Total gross electrical power	7.23 MWe
Total pumping power	1.42 MWe
ORC Working fluid	Isobutane
Conversion efficiency of thermal energy into electricity	13.1%
Electrical power per well	1.67 MWe

3.2 The wellbore heat exchanger

The WellBore Heat eXchanger device is a deep borehole heat exchanger (Fig. 3). The bottom of the well is closed and a coaxial tube is inserted into the well; in the WBHX a heat carrier fluid is circulated and acquires heat from the surrounding rock.

Several researchers have analyzed the feasibility of the WBHX, the operative parameters and the application of the different heat carrier fluids (Kohl et al., 2002; Kujawa et al., 2006; Zhang, 2008; Davis and Michaelides, 2009; Bu et al., 2012; Cheng et al., 2013; Cheng et al., 2014; Templeton et al., 2014; Alimonti and Soldo, 2016).

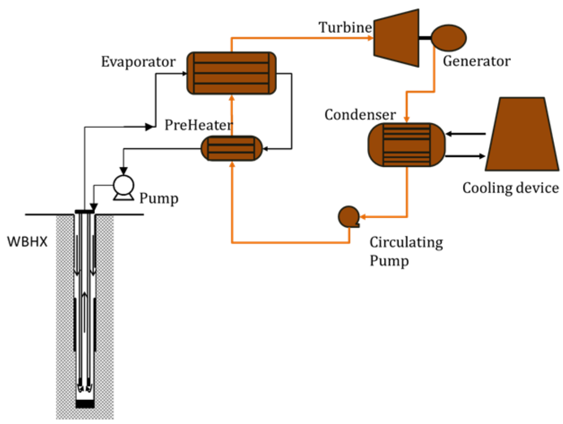

Figure 3: WBHX and ORC plant scheme.

In the proposed solution (Alimonti and Soldo, 2016), water has been selected as the best heat carrier fluid, due to its comparably high volumetric heat capacity. The water circulates in the annular space between the well casing and the external shell. Flowing downward, the fluid acquires the heat. At the well bottom the heated water flows into the inner pipe due to the thermo-siphon effect and it flows back to the wellhead naturally. Therefore, no electricity is required to pump the fluid upwards. The space between the two pipes is filled with insulating material. The extracted heat is converted into electricity using an Organic Ranking Cycle plant (Fig. 4). For further details see Alimonti et al., 2016).

The deep borehole heat exchanger has been applied in the well Mofete 3d (MF3d). In order to evaluate the physical and thermal properties of the area (Tab. 2 and Tab. 3), the work of Carlino et al. (2012) has been used. The medium geothermal gradient is almost 155 °C/km.

Using numerical simulations, the configuration which ensures greater efficiency in heat extraction for this specific case study has been obtained. (Tab. 4).

Table 2: Lithology and geothermal gradients of MF3d well.

Thick. (m)	Depth (m)	T (°C)	Lithology	GT (°C/100 m)
240	240	165	Pyroclastic deposits	47.92
500	740	230	Tuff	13
200	940	255	Tuff-Trachytic lava	12.5
390	1290	300	Trachytic lava	12.86

Table 3: Physical and thermal properties of MF3d well.

Lithology	ρ (kg/m3)	λ (W/m K)	cp (J/kg K)
Pyroclastic deposits	1800	2.90	840
Tuff	1550	1.50	2000
Tuff-Trachytic lava	2025	2.20	1420
Trachytic lava	2500	2.90	840

Table 4: This is a table title, bold, 6 pt space before and after, after, indented from the second line on by 0.95 cm.

	Outer diam.	Inner diam.
External Casing 7"	177.8 mm	150.3 mm
External pipe 5 ½"	139.7 mm	121.4 mm
Internal pipe 3 ½"	88.9 mm	77.9 mm

The simulations highlight that, after six months a thermal power production of almost 2.5 MW per well may be expected. In Table 5 the principal characteristics of the proposed plant are presented.

Table 5: WBHX-ORC power plant

Type of plant	WBHX-ORC
Size of plant	5 MWe
Number of production wells	20
Number of injection wells	0
Depth of well	1909 m
Flow rate	20 m^3/h
Wellhead temperature	150 °C
Reinjection temperature	40 °C
Thermal power per well	2.5 MW
ORC Working fluid	Decafluoro-butene
η %	10.34%
Electrical power per well	250 kWe

4. BUILDING INDICES FOR THE SELECTION MATRIX

To evaluate the better technology to be adopted in the geothermal power plant of Scarfoglio, the obtained performance index with the following relationship was applied:

$$P = \frac{\sum_{j=1}^{N} (I_j \cdot w_j)}{N} \quad [1]$$

A set of eleven indices has been developed. Each index I_j has a value between 0 and 1. The 0 represents an unfavorable and 1a highly favorable situation. The assigned weight of the Indices are indicated by w_j. The number of indices is represented as N.

4.1 Technical and engineering indices

Following the indices, which evaluate the technical and engineering features of the project, are explained.

4.1.1 Electrical power production index I_p

A reference value (Pr) of 5 MWe has been selected, which is used (Vimmerstedt L., 1998; Lund and Boyd, 1999; Franco and Villani, 2009) as the maximum installed power for small sized binary power plants. A value between 0.5 MW and 5 MW has been chosen for the evaluated electrical power (P) using the data of the binary power plants in the world collected by Di Pippo (2012). In Table 6 the ranking values for electrical power production indices are reported.

4.1.2 Exergetic Availability index I_{EA}

The exergetic availability can be defined with the following relation (Franco and Villani; 2009):

$$\frac{E_x}{E_{x0}} = \frac{(T_{geo} - T_{rej}) - T_0 \ln(T_{geo}/T_{rej})}{(T_{geo} - T_0) - T_0 \ln(T_{geo}/T_0)} \quad [2]$$

Where T_{geo} is the geothermal fluid inlet temperature, T_{rej} is the reinjection temperature, T_0 is standard condition temperature (25 °C).

According to Maghiar and Antal (2001) the binary systems work with temperatures in the range between 85 ÷ 170 °C. The report on the future of geothermal energy edited by MIT (2006) indicates that real binary power plants in the world work with an inlet temperature in a range of 105 ÷ 165 °C. Therefore, a range between 80 ÷ 180 °C has been selected for this analysis.

Franco and Villani (2009) report that the reinjection temperature of the binary power plants is between 50 °C and 110 °C; according to Diaz et al. (2015), the reinjection temperatures for medium-enthalpy, liquid-dominated systems are in the range of 30 ÷ 175°C. Considering the selected range for the inlet temperature, an interval of 30 ÷ 110 °C has been used for the reinjection temperature. In Table 7 the values of the exergetic availability index are shown.

4.1.3 Temperature-flow rate index I_{QT}

The thermal power depends on the flow rate and temperature of the produced fluid. For these reasons, an indicator, based on the ratio between the fluid flow rate (q) and its flowing temperature at wellhead (T_E), has been proposed.

The wellhead fluid temperature has been already fixed. For the flow rate values, the study of Franco and Villani (2009) has been used: the authors collected the values of specific brine consumption for some small sized binary power plants (≤ 1 MWe). The specific brine consumption is between 14.7 kg $s^{-1}MW^{-1}$ and 86 kg $s^{-1}MW^{-1}$, which corresponds to a flow rate between 52 and 520 m^3/h. Ranking values between 50 and 500 m^3/h of the temperature-flow rate index a have been assigned (Tab.8).

4.1.4 Specific brine consumption index I_{BC}

Greater brine consumption at equal produced power, implicates greater costs, especially for the reinjection operations. Therefore, a specific brine consumption index is proposed (Tab. 9). According to the data collected by Franco and Villani (2009), a range of 10 ÷ 100 kg $s^{-1}MW^{-1}$ has been selected for the specific brine consumption (q_{spec}).

4.1.5 Outlet temperature index I_{Texit}

The outlet temperature of the fluid at the wellhead is one of the main parameters of a geothermal power plant. To account its relevance a parameter, which relates the wellhead temperature of the fluid with a characteristics temperature of the energy conversion plant, has been defined.

In our analysis the conversion plant is an ORC machine which operates with entrance temperatures between 80 and 170 °C (VV.AA. MIT Report, 2006; Franco and Villani, 2009). Therefore, the characteristic temperature is defined as the minimum inlet temperature of the fluid into the ORC machine (80 °C) and the wellhead temperature of the fluid (T_E) varies between 80°C and 180°C. In Table 10 the ranking values of the outlet temperature are shown.

4.1.6 Pumping aided production index I_{PE}

The request of pumping is obviously a reduction in energy efficiency of the power plant generation. The index to rank the technology is defined on the ratio between the pumping energy and the produced energy. Therefore, assuming that a project plant is inconvenient if the pumping energy E_p is higher than 20% of the produced energy E, a range between 0% and 20% has been fixed (Tab.11).

4.1.7 Scaling-Corrosion index in production wells I_{SC}

The scaling and corrosion phenomena are frequent, both in reinjection and in production wells. These phenomena are related to the chemical composition of the brine, the pH value, the pressure and temperature changes and the oversaturation of some dissolved minerals. Corrosion and scaling can cause damages to pipes, result in a reduction of casing diameters lead to an efficiency decrease of the geothermal well. Maintenance operations and additional investments will be necessary.

The corrosion and scaling index in the production wells I_{SC} (Tab. 12) is based on the modulus of the Langelier index, calculated by the difference between the pH of water and the saturation pH of the calcium carbonate (pHs).

4.1.8 Reinjection index I_I

Due to the different aspects that concern the fluid reinjection process, the reinjection index will be obtained by considering the following sub-Indices.

I_{IC}: accounts for the injection operation costs and is evaluated by using the percentage of the relation between the pumping power (P_{inj}) and the gross power (P). Regarding the operation costs of the reinjection, Franco & Villani (2009) report that a percentage between 10% and 20% of the gross power is absorbed by a dry cooling system under ideal conditions; if the reinjection temperature is near the ambient temperature, the absorbed power can grow up to 40% or 50% of the gross power. Starting from these values, the injection costs index has been elaborated (Tab. 13).

I_{ISC} takes the corrosion and scaling phenomena in the injection wells into account. In the reinjection wells the scaling phenomena are more recurring due to the relative low temperature (generally < 90°C). The index is based on the modulus of Langelier index, as is the scaling and corrosion index in the production wells (Tab. 14).

I_{ITP} is the thermal pollution-injection index. It considers the hazard of decrease in brine temperature when the production and the reinjection wells are close. The geothermal reservoir of Campi Flegrei is a medium enthalpy system. The key element to quantify the thermal pollution-injection index (Tab. 15) has been considered to be the distance between the production and the reinjection zone (DPR), which is between 0.4 and 4 km in the medium enthalpy power plants (Diaz et al., 2015).

I_{IT} is the index of the reinjected fluid temperature. In Table 16 the ranking is displayed: a lower value has been assigned to the lower temperatures because of the risk of corrosion, the risk of cooling the productive layers and the greater electrical power request for the condensers.

Following some indices are explained, for which a quantitative ranking has not yet been obtained. Therefore, a qualitative assessment is proposed.

I_{ICC} accounts for the risk of chemistry changes in reservoir fluids when the brine is flashed (Stefansson (1997). After the flashing, only the separated water is injected, which has a higher concentration of dissolved solids, but lower gas content. If hazard is present, the index will be equal to zero, if absent it will be set to one.

I_{ID} considers the depth of injection. If the injection could be in the same layer as production, the index will be equal to one, if not it will be zero.

The value of the Injection index is the weighted average of the sub-indices:

$$I_I = \frac{\sum_{j=1}^{M}(I_{Ij} \cdot w_j)}{M} \quad [3]$$

I_{Ij} is the sub-index, w_j is the assigned weight and M is the number of sub-indices.

4.2 Environmental and social indices

4.2.1 Environmental impact index I_{ENV}

The environmental impact index is calculated by the average of the Boolean sub-indices:

$$I_{ENV} = \frac{\sum_{j=1}^{K}(I_j \cdot w_j)}{K} \quad [4]$$

where I_j is the sub-index, w_j is the assigned weight and K is the number of sub-indices.

The environmental evaluation takes care only of the impacts during the operational of the plants; the environmental effects, related to the drilling and the construction of the field, in our case study are similar for both type of power plant. Therefore, they are not significant in the comparison between the two extraction technologies.

Following the applied sub-Indices of the Selection Matrix 2.0 are listed.

I_S represents the sustainably index. In the geothermal energy development, the sustainability is related to the equilibrium between energy extraction (production) and the natural recharge of the reservoir (Franco and Vaccaro; 2012). Therefore the reinjection of spent water or condensed steam is a method to increase the sustainability of the geothermal plant (Cataldi, 2001; Rybach, 2003). For this reason, a sustainability index I_s, related to the ratio between injection flowrate and production flowrate, has been proposed (Tab. 17). The ranking values are based on the injection-production ratio of existing power plants reported by Axelsson (2012).

I_{AIR} is the index of gas emissions in atmosphere. According to Hunt (2000), the amount of greenhouse gas emissions from geothermal power plants, expressed as CO_2 equivalents, reaches a maximum value of 400 kg/MWh, therefore the ranking values reported in Table 18 have been proposed.

I_{PH} is the environmental index for potential earthquakes. The occurrence of seismicity phenomena induced by plant operations is a critical point in the evaluation of the feasibility of a geothermal power plant, due to the possible damages and human losses in the vicinity of the plant. A potential earthquake index I_{PH}, based on the peak ground acceleration (PGA) and on the energy production system, has been proposed. To establish the ranking values (Tab. 19), the starting point is the seismic assessment of Italy, the territory of which is classified into four zones, depending on the value of the PGA. The high-risk seismic zone has a PGA > 0.25 g, the much low-risk seismic zone has a PGA < 0.05 g.

I_{SU} is the soil use index. According to the data reported in Di Pippo (2012) the geothermal power plants have the smallest land footprint compared to the other technologies (hydrocarbons, nuclear, hydroelectric and solar plant, wind farm). Therefore the soil use has been considered positive for all the geothermal power plants.

I_{WVL} is the index of disturbance of wildlife habitat, vegetation and view of the landscape, which was related with the land footprint of the power plant. Given the small size of the closed loop binary power plant and the lower dimension of the cooling towers requested by the dual flash plant, in respect to the single flash and the dry steam power plant, the ranking in Table 20 has been proposed.

I_N is the noise index. The noise of a geothermal plant during normal operational should not be unpleasant to the population living nearby (Di Pippo, 2012). Therefore a positive value has been assigned to the index.

I_{WP} considers the potential water pollution. The geothermal brines may contain minerals and elements (e.g. boron, arsenic, mercury), hazardous for groundwater and surface water. According to Di Pippo (2012), the dissolved solid concentration increases with temperature, so a high temperature of geothermal fluid is more risky than a moderate or low temperature. The pollution may occur when damaged casings allow the contact between geothermal fluid and groundwater, or when there is an accidental surface runoff of the waste brine which might reach surface waters (river or lake). A reinjection of 100% of the waste brine, as well as an extraction of thermal energy without brine production, reduces the risk of water pollution. The water pollution index is calculated as the average value of the qualitative sub-indices which are explained in Table 21.

I_{LS} is the land subsidence index. When the fluid production exceeds the recharge rate of the reservoir, subsidence phenomena may take place. The risk of land subsidence is greater in a pore-dominated and permeable reservoir than in formations where the fluid is under the lithostatic rather than hydrostatic pressure (Di Pippo, 2012) and in water-dominated fields. The use of reinjection can reduce the risk of land subsidence. Therefore the semi-qualitative index has been proposed (Table 22): the land subsidence index is the average value of the sub-indices.

4.2.2 Social impact index I_{SI}

The social impact on the realization and viability of a plant represents an issue. The increasing concern of communities adjacent to the field itself led to the implementation of social acceptance as one factor of a project.

The complexity of the subject forces to define the index in a semi-qualitative form. The social impact is related to several aspects of the project, which have been assigned into three categories: the project benefits (e.g. job opportunities, decrease of energy cost for the population, royalties), the environmental impact and the impact on human health of the population near the power plant.

Therefore, the social impact I_{SI} is the average of three sub-indices, presented in Table 23.

4.3 Economic index

For the assignment of a score to the cost index I_C, the payback time of the investment has been chosen as parameter. According to Kenny et al (2010), the payback time of a geothermal plant is 6 years. Therefore, a highly positive value has been assigned if the payback time is shorter than 6 years and is of no interest if the payback time equals or exceeds 10 years (Tab. 24).

5. APPLICATION OF THE SELECTION MATRIX2.0

Seven technical indices (I_P, I_{EA}, I_{QT}, I_{BC}, I_{Texit}, $I_{PE,}$ I_{IT}) have been evaluated using the technical data of the CUMA pilot project and WBHX power plant (Table 1 and 5).

In order to calculate the scaling-corrosion indices in the production (I_{SC}) and injection wells (I_{ISC}), the following chemical parameters of the study area were used (Table 26; Carella and Guglielminetti, 1987).

Table 26: WBHX-ORC power plant

pH acqua	6
TDS (ppm)	37880
Ca (ppm)	889
Mg (ppm)	7.9
CaCO3 (ppm)	2270.802
Al≈HCO3 (ppm)	85
As (ppm)	22
Hg (ppm)	<0.0004
B (ppm)	295
pH acqua	6
TDS (ppm)	37880

Regarding the WBHX plant, no injection is needed thanks to the thermo-siphon effect. Therefore, a positive value has been assigned to the following indices: the injection operations costs index (I_{IC}), the scaling-corrosion index in the injection wells (I_{ISC}) and in the production wells (I_{SC}), the depth of injection location index (I_{ID}), the sustainability index (I_S) and the potential earthquakes index IPH.

In the binary power plant the total amount of extracted brine is injected back into the production layer, hence I_{ID} and I_S have a positive value.

The scaling-corrosion index in the injection wells (I_{ISC}) is equal to the one in the production wells.

The thermal pollution injection index (I_{ITP}) is low for both of the power plants. The dimension of the Cuma project area is relatively small (6 X 14 m) and therefore one of the production wells is located in the close vicinity of two reinjection wells. Besides the fact that the wells of the Cuma field are deviated, the distance between the production and the reinjection zone is lower than 1.5 km. In the deep borehole exchanger no production of geothermal fluids takes place, but there is the risk of cooling the ground in the vicinity of the WBHX, considering the great number of exchanger wells (20) in this restricted area.

As no flashing of geofluids occurs in binary power plants, the risk of chemical changes is absent, as well as for the WBHX (I_{ICC} equal to zero).

The selection of the two closed loop plants guarantees that no emission or leakage occurs, causing no disruption of wildlife habitat, vegetation and view of the landscape. Therefore, a positive value has been assigned to I_{AIR} and I_{WVL}.

The maximum value has been assigned to the soil use index I_{SU}, as well as to the noise index $I_{N,}$ for all geothermal power plants.

For the binary power plant the potential earthquakes index I_{PH} is related to the seismic classification of the Campi Flegrei area (PGA=0.15g ÷ 0.75g).

In the study area, there is an important underground hydrothermal system, which is critical for the thermal activities and the presence of thermo-mineral springs. Due to certain chemical elements in the geothermal brine, such as As, Hg and B (Table 26; Carella & Guglielminetti, 1987), the potential water pollution index (I_{WP}) is not positive for neither the binary power plant nor for the WBHX.

In order to evaluate the social impact index (I_{SI}), the hypothesis of possible benefits of the project and the lack of risks for human health was taken into consideration for both technological solutions.

Regarding the calculation of the cost index, an economic evaluation of the project was conducted (Table 27), using the cost data stated in the documents of the Cuma pilot project. The cost of energy, used to estimate the cash flow, is 0.16 €/kWh (price per customer in Italy).

Table 28 displays the injection and environmental Indices and their sub-indices. The injection index is equal for the two technological solutions; the environmental impact of the borehole heat exchanger is less than of the binary power plant.

Table 27: Economic evaluation of the projects

	Binary power plant	WBHX power plant
Electrical plant	€ 190,000	€ 190,000
ORC 5 MWe	€ 12,500,000	€ 12,500,000
Well drilling and completion	€ 4,830,000	€ 27,720,000
Wells and power plant area	€ 850,000	€ 850,000
Brine pipes	€ 230,000	€ 276,000
Pumping energy	€ 1,799,424	€ 2,500
Ordinary Maintenance (electrical plant)	€ 500,000	€ 500,000
Extraordinary Maintenance	€ 96,600 scaling/corrosion 2% drilling cost	€ 35,000 Water and additives
Capital cost	**€ 186,00,000**	**€ 41,573,500**
Annual cost	**€ 2,396,024**	**€ 500,000**
Produced energy per year	**39,600 MWh**	**39,600 MWh**
Annual revenue	**€ 6,336,000**	**€ 6,336,000**
Payback time	**4.08 years**	**7.48 years**

Table 28: Injection and Environmental index

Injection index			
INDEX	**Doublet**	**WBHX**	**Weight**
I_{IC}	1	1	1
I_{ISC}	0	1	1
I_{ITP}	0.4	0	1
I_{IT}	0.6	0.2	1
I_{ICC}	1	1	1
I_{ID}	1	1	1
$\mathbf{I_I}$	**0.7**	**0.7**	
Environmental index			
INDEX	**Doublet**	**WBHX**	**Weight**
I_S	1	1	1
I_{AIR}	1	1	1
I_{PH}	0.6	1	1
I_{SU}	1	1	1
I_{WVL}	1	1	1
I_N	1	1	1
I_{WP}	0.5	1	1
I_{LS}	1	1	1
$\mathbf{I_{ENV}}$	**0.9**	**1.0**	

The aim of the work is to supply an instrument to evaluate two geothermal power plants, as well as to highlight that the result of the evaluation depends on the weight the decision maker assigns to the indices, considering the specific characteristics of the territory where the plant is realized. The decision maker may assign the same value to all the Indices or may emphasize the importance of some features.

Therefore, three scenarios have been proposed: in the base case scenario all indices have the same value equal to 1 (Tab. 29); in the social and environmental friendly scenario a value of 2 is assigned to the environmental index social indices (Tab. 30); in the techno-economic scenario a double weight is assigned to the cost index and to the production indices I_P and I_{Texit} (Tab. 31).

Table 29: Selection Matrix 2.0 – Campi Flegrei: base case scenario

Matrix2.0 – Base case scenario			
INDEX	**Doublet**	**WBHX**	**Weight**
I_p	0.4	0	1
I_{EA}	0.6	1	1
I_{qT}	0.6	1	1
I_{BC}	0.8	1	1
I_{Texit}	1	0.6	1
I_{PE}	0.2	1	1
I_{SC}	0	1	1
I_I	0.7	0.7	1
I_{ENV}	0.9	1	1
I_S	0.6	0.7	1
I_C	1	0.6	1
P	**0.6**	**0.8**	

Table 30: Selection Matrix 2.0 – Campi Flegrei: Social and environmental friendly scenario

INDEX	**Doublet**	**WBHX**	**Weight**
I_p	0.4	0	1
I_{EA}	0.6	1	1
I_{qT}	0.6	1	1
I_{BC}	0.8	1	1
I_{Texit}	1	0.6	1
I_{PE}	0.2	1	1
I_{SC}	0	1	1
I_I	0.7	0.7	1
I_{ENV}	0.9	1	2
I_S	0.6	0.7	2
I_C	1	0.6	1
P	**0.8**	**0.9**	

Table 31: Selection Matrix 2.0 – Campi Flegrei: Techno-economic scenario

Matrix2.0 – Base case scenario			
INDEX	**Doublet**	**WBHX**	**Weight**
I_p	0.4	0	*2*
I_{EA}	0.6	1	*1*
I_{qT}	0.6	1	*1*
I_{BC}	0.8	1	*1*
I_{Texit}	1	0.6	*2*
I_{PE}	0.2	1	*1*
I_{SC}	0	1	*1*
I_I	0.7	0.7	*1*
I_{ENV}	0.9	1	*1*
I_S	0.6	0.7	*1*
I_C	1	0.6	*2*
P	**0.8**	**0.9**	

The application of the Selection Matrix2.0 highlights the superior project performance for the application of a wellbore heat exchanger in the Campi Flegrei area, compared to a binary power plant. Even when emphasizing the impact of a single feature of the plant (social-environmental or techno-economical), the difference between the final scores of the two projects is only 0.1%.

6. CONCLUSIONS

This article proposes an updated version of the Selection Matrix (Soldo & Alimonti, 2015) to identify the best extraction technology for the geothermal energy recovery from the Campi Flegrei area. Two technologies are presented and evaluated: a binary power plant with a production and injection well and a deep borehole heat exchanger power plant without geofluid production. To quantify all the aspects that characterize the two projects, ranging from technical to economic, environmental and social issues, a system of thirteen indices, fourteen sub-indices and weights has been introduced. The final score is calculated using the weighted average of the indices which have a value between 0 (unfavorable) and 1 (highly favorable) each. The selection of the most applicable technological solution for a project depends on the assigned weight to the indices. Three different scenarios have been proposed. The base case scenario assigns equal weight to all indicators. The techno-economic scenario assigns a major weight to the cost index and to production indices. The third scenario is social and environmental friendly. For all scenarios the WBHX remains the best choice, even though its performance outweighs the binary power plant only by 0.1% for both scenarios.

TABLES

Table 6 - Electrical energy production index

Range	$P/P_r<0.1$	$0.1\leq P/P_r<0.2$	$0.2\leq P/P_r<0.4$	$0.4\leq P/P_r<0.6$	$0.6\leq P/P_r<1$	$P/P_r\geq 1$
I_P	0	0.2	0.4	0.6	0.8	1

Table 7 - Exergetic Availability index

Range	$E/E_{x0}<0.5$	$0.5\leq E/E_{x0}<0.6$	$0.6\leq E/E_{x0}<0.7$	$0.7\leq E/E_{x0}<0.8$	$0.8\leq E/E_{x0}<0.9$	$E/E_{x0}\geq 0.9$
I_{EA}	0	0.2	0.4	0.6	0.8	1

Table 8 - Temperature-flow rate index

Range ($m^3h^{-1}°C^{-1}$)	$q/T_E\geq 6.25$	$3.18\leq q/T_E<6.25$	$1.79\leq q/T_E<3.18$	$0.94\leq q/T_E<1.79$	$0.28\leq q/T_E<0.94$	$q/T_E<0.28$
I_{qT}	0	0.2	0.4	0.6	0.8	1

Table 9 – Specific brine consumption index

Range ($kg\ s^{-1}MW^{-1}$)	$q_{spec}\geq 100$	$80\leq q_{spec}<100$	$60\leq q_{spec}<80$	$30\leq q_{spec}<60$	$10\leq q_{spec}<30$	$q_{spec}<10$
I_{BC}	0	0.2	0.4	0.6	0.8	1

Table 10 - Outlet temperature index

Range	$\frac{T_E}{T_{ORC}}<1$	$1\leq\frac{T_E}{T_{ORC}}<1.38$	$1.38\leq\frac{T_E}{T_{ORC}}<1.75$	$1.75\leq\frac{T_E}{T_{ORC}}<2$	$2\leq\frac{T_E}{T_{ORC}}<2.25$	$\frac{T_E}{T_{ORC}}\geq 2.25$
I_{Texit}	0	0.2	0.4	0.6	0.8	1

Table 1- Pumping aided production index

Range	$E_p/E>0.2$	$0.15<E_p/E\leq 0.2$	$0.1<E_p/E\leq 0.15$	$0.05<E_p/E\leq 0.1$	$0<E_p/E\leq 0.05$	$E_p/E=0$
I_{PE}	0	0.2	0.4	0.6	0.8	1

Table 22 - Corrosion and scaling index in the production wells

Range	$\lvert LSI\rvert=2$	$1.5<\lvert LSI\rvert<2$	$1<\lvert LSI\rvert\leq 1.5$	$0.5<\lvert LSI\rvert\leq 1$	$0<\lvert LSI\rvert\leq 0.5$	$\lvert LSI\rvert=0$
I_{SC}	0	0.2	0.4	0.6	0.8	1

Table 3 – Injection costs index

Range	$P_{inj}/P\geq 0.5$	$0.4\leq P_{inj}/P<0.5$	$0.3\leq P_{inj}/P<0.4$	$0.2\leq P_{inj}/P<0.3$	$0.1\leq P_{inj}/P<0.2$	$P_{inj}/P<0.1$
I_{IC}	0	0.2	0.4	0.6	0.8	1

Table 4 - Corrosion and scaling index in the reinjection wells

Range	$\lvert LSI\rvert=2$	$1.5<\lvert LSI\rvert<2$	$1<\lvert LSI\rvert\leq 1.5$	$0.5<\lvert LSI\rvert\leq 1$	$0<\lvert LSI\rvert\leq 0.5$	$\lvert LSI\rvert=0$
I_{ISC}	0	0.2	0.4	0.6	0.8	1

Table 55 – Risk index of thermal pollution

Range (km)	D_{PR}<0.4	0.4≤D_{PR}<1	1≤D_{PR}<2	2≤DPR<3	3≤D_{PR}<4	D_{PR}≥4
I_{ITP}	0	0.2	0.4	0.6	0.8	1

Table 66 – Index of reinjected fluid temperature

Range (°C)	T_{rf}<30	30≤T_{rf}<50	50≤T_{rf}<70	70≤T_{rf}<90	90≤T_{rf}<110	T_{rf}≥110
I_{IT}	0	0.2	0.4	0.6	0.8	1

Table 7 - The sustainability index

Range (g)	R_{i-p}<0.1	0.1≤R_{i-p}<0.3	0.3≤R_{i-p}<0.5	0.5≤R_{i-p}<0.7	0.7≤R_{i-p}<0.9	R_{i-p}≥0.9
I_S	0	0.2	0.4	0.6	0.8	1

Table 18 - Air emissions index

Range (kg/MWh)	CO_2≥100	40≤CO_2<100	30≤CO_2<40	20≤CO_2<30	10≤CO_2<20	CO_2<10
I_{AIR}	0	0.2	0.4	0.6	0.8	1

Table 19 – The potential earthquakes index

I_{PH}	No brine extraction/injection operations I_{PH} =1			Brine extraction/injection operations I_{PH}=I_{PGA}		
Range (g)	PGA≥0.25	0.2≤PGA<0.25	0.15≤PGA<0.2	0.1≤PGA<0.15	0.05≤PGA<0.1	PGA≤0.05
I_{PGA}	0	0.2	0.4	0.6	0.8	1

Table 8 - Wildlife habitat, vegetation and view of the landscape index

Type of plant	Single flash steam plant Dry steam plant	Closed loop binary power plant Dual flash steam plant
I_{WVL}	0.5	1

Table 9 – Water pollution index evaluation

Ranking	0	0.5	1
Brine temperature		High	Medium or low
Dissolved solids	As, Hg, B present		As, Hg, B absent
Reinjection%	< 70% of waste brine		≥ 70% of waste brine
Extraction technology		Brine production	Heat exchanger
Groundwater	Presence of a critical aquifer		Absence of a critical aquifer

Table 10 – Land subsidence index evaluation

Ranking	I_s	1
Permeability	Pore-dominated	Fracture-dominated
Pressure	Lithostatic	Hydrostatic
Reservoir	Water-dominated	Vapour-dominated

Table 113 – Social impact sub-indices

Sub-indices	Ranking	
Project benefits	0 = no expected project benefits	1 = possibility of project benefits
Human health	0 = risk for human health	1 = no risk for human health
Environmental impact	I_{ENV}	

Table 124 - Cost index

Range	t_{pb} ≥10 y	9 y≤t_{pb}<10 y	8 y≤t_{pb}<9 y	7 y≤tpb<8 y	6 y≤t_{pb}<7 y	t_{pb}<6 y
I_C	0	0.2	0.4	0.6	0.8	1

REFERENCES

Alimonti, C. and Soldo, E.: Study of geothermal power generation from a very deep oil well with a wellbore heat exchanger, *Renewable Energy*, **86,** (2016), 292-301.

Axelsson G: Role and management of geothermal reinjection. *Presented at Short Course on Geothermal Development and Geothermal Wells 2012*, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, (2012), 1-21.

Bu, X., Ma, W., Li, H.: Geothermal energy production utilizing abandoned oil and gas wells, *Renewable Energy*, **41,** (2012), 80-85.

Carella, R., Giglieliminetti, M., Verdiano, G.: Attività dell'AGIP nel campo dell'energia geotermica in Italia. Convegno della Federelerrica, Padova 10 Aprile, (1986).

Carlino, S., Somma, R., Troise, C., De Natale, G.: The geothermal exploration of Campanian volcanoes: Historical review and future development, *Renewable and Sustainable Energy Reviews*, **16,** (2012), 1004–1030.

Cataldi, R.: Sustainability and renewability of geothermal energy. In: *Proceedings of the International Scientific Conference on Geothermal Energy in Underground Mines,* Ustron, Poland, (2001).

Cheng, W.L., Li, T.T., Nian, Y.L., Wang, C.L.: Studies on geothermal power generation using abandoned oil wells, *Energy*, **59,** (2013), 248-254.

Cheng, W.L., Li, T.T., Nian, Y.L., Wang, C.L.: Evaluation of working fluids for geothermal power generation from abandoned oil wells, *Applied Energy*, **118,** (2014), 238-245.

Costa, A., Dell'Erba, F., Di Vito, M.A., Isaia, R., Macedonio, G., Orsi, G., Pfeiffer, T.: Tephra fallout hazard assessment at the Campi Flegrei caldera (Italy). *Bull Volcanol*, **71**, (2009), 259–273 DOI 10.1007/s00445-008-0220-3.

Davis, A.P. and Michaelides, E.E.: Geothermal power production from abandoned oil wells, *Energy*, **34,** (2009), 866–872.

Di Pippo, R., Geothermal Power Plants – Third Edition, *Elsevier*, 2012.

Diaz, A.R., Kaya, E., Zarrouk, S.J.: Reinjection in Geothermal Fields: A Worldwide Review Update. *Proceedings of World Geothermal Congress 2015*, Melbourne, Australia, (2015).

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

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

Hettiarachchi HDM, Golubovica M, Woreka WM, Ikegamib Y: Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources, *Energy*, **32,** (2007), 1698–1706.

Kenny, R., Law, C., Pearce, J.M.: Towards Real Energy Economics: Energy Policy Driven by Life-Cycle Carbon Emission, *Energy Policy*, **38**, (2010), 1969–1978.

Kohl, T., Brenni, R., Eugster, W.: System performance of a deep borehole heat exchanger, *Geothermics*, **31,** (2002), 687–708.

Kujawa, T., Nowak, W., Stachel, A.A.: Utilization of existing deep geological wells for acquisitions of geothermal energy, *Energy*, **31,** (2006), 650–664.

Lund, J.W., Boyd, T.: Small geothermal power projects examples. *Geo-Heat Center Quarterly Bulletin*, **20 (2)**, (1999), 9–26.

Maghiar, T. and Antal, C.: Power generation from low-enthalpy geothermal resources, *GHC Bulletin, June 2001*, (2001).

Nalla, G., Shook, G.M., Mines, G.L., Bloomfield, K.K.: Parametric sensitivity study of operating and design variables in wellbore heat exchangers, *Geothermics*, **34,** (2005), 330–346.

Rybach, L.: Geothermal energy: sustainability and the environment, *Geothermics*, **32**, (2003), 463–470.

Soldo, E. and Alimonti, C.: From an oilfield to a geothermal one: use of a selection matrix to choose between two extraction technologies. *In Proceedings World Geothermal Congress 2015*, Melbourne, Australia, (2015), 1-10, ISBN:978-1-877040-02-3.

Stefansson, V.: Geothermal reinjection experience, *Geothermics*, **26**, (1997), 99-139.

Templeton, J.D., Ghoreishi-Madiseh, S.A., Hassania, F., Al-Khawaja, M.J.: Abandoned petroleum wells as sustainable sources of geothermal energy, *Energy*, **70,** (2014), 366–373.

Vimmerstedt, L.: Opportunities for Small Geothermal Projects: Rural Power for Latin America, the Caribbean, and the Philippines, November 1998, NREL/TP-210-25107.

VV.AA.: The Future of Geothermal Energy – Impact of Enhanced Geothermal System (EGS) on the United States in the 21th Century, MIT-Massachusetts Institute of Technology, USA, (2006).

Zhang, L., Yuan, J., Liang, H., Li, K.: Energy from Abandoned Oil and Gas Reservoirs. *Proceedings of Asia Pacific Oil and Gas Conference and Exhibition 2008*, Perth, Australia, (2008).

Zollo, A., Maercklin, N., Vassallo, M., Dello Iacono, D., Virieux, J., Gasparini, P.: Seismic reflections reveal a massive melt layer feeding Campi Flegrei caldera, *Geophys.Res.Lett.*, **35,** (2008) L12306, doi:10.1029/2008GL03424.