Social-Multi Criteria Evaluation of Alternative Geothermal Power Scenarios: The case of Mt. Amiata in Italy

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Abstract

Italy was the first country in the world to exploit geothermal resources for the production of electricity. In Europe it is still the first country in terms of installed capacity. Currently, the only region in Italy with geothermal power plants is Tuscany. This study focuses on Mt. Amiata, one of the two geothermal areas in Tuscany, where there is strong opposition to the exploitation of geothermal resources. The context is characterized by contested scientific results regarding crucial issues such as the impact of geothermal exploitation, the conservation of water resources and human health. A social multi-criteria evaluation is proposed to explore the different legitimate perspectives of the actors involved. Scenarios are distinguished in terms of their installed capacity, technology and plant site. A Condorcet consistent aggregation algorithm is applied and results are analyzed using a sensitivity analysis. The alternative scenarios are evaluated in a multi-dimensional way by attaching different weights to the criteria reflecting divergent points of view.

Keywords: geothermal power, multi-criteria analysis, integrated assessment, conflict analysis, Italy

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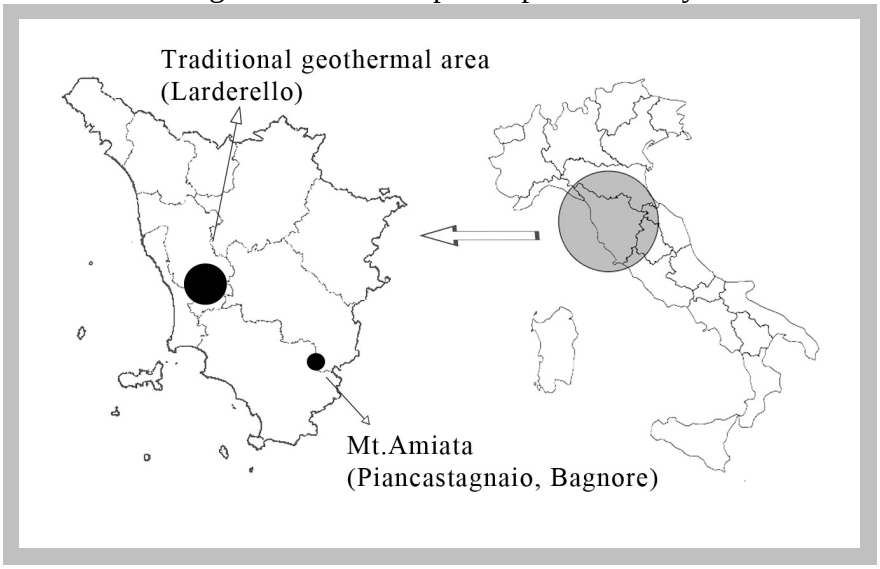
1. Introduction

This paper intends to show the potential use of a social multi-criteria evaluation (SMCE) in managing problems related with conflicts arising around geothermal power. Specifically, it explores the case of Mt. Amiata, in the region where geothermal power originated: Tuscany.

The first experiments to use geothermal energy to produce electricity took place in Tuscany in 1904 in Larderello. Since then Italy has remained the first producer of electricity from geothermal sources in Europe and is the fifth internationally after the USA, Philippines, Indonesia, and Mexico (Bertani and Fridleifsson, 2010). At the moment of writing all the geothermal power plants in Italy are located in Tuscany. Here geothermal power made up 24% in 2009 of electricity consumption (and 32% of net production), while nationally the contribution of geothermal power to electricity consumption is just 1.6% (Terna, 2010). Currently there are 35 power plants with 882,5 MW of installed capacity[1] (ARPAT, 2010; ENEL, 2010). In Tuscany the geothermal power plants are located in two areas: the so-called traditional area around Larderello where 30 plants (and 794,5 MW of installed capacity) are located, and Mt. Amiata area (in the south of Tuscany) where five plants (with 88MW) have been installed (see Fig. 1). It is in the Mt. Amiata area where geothermal energy has been facing strong opposition during the last few years.

Fig. 1: Geothermal power plants in Italy



Opposition to renewable energies is not uncommon and it is often considered as a NIMBY (not in my back yard) attitude. The geothermal power industry therefore tends to classify such behavior as a social acceptability problem (Cataldi, 2001; De Jesus,

[1] Corresponding to 770 MW of net capacity.

1997). However more than simple social acceptability, opposition should be considered as being part of a more general environmental management problem which presents elements of energy policy, economic considerations, local pollution, water conservation concerns, employment effects, quality of life and aesthetical aspects. This kind of environmental management problem reflects conflicts of interests and values. In the presence of plural values, incommensurability is the norm and not the exception. Incommensurability refers to the absence of a common unit of measurement to evaluate alternatives (Martinez-Alier et al., 1998). This is because simply deciding what to measure implies value conflicts. However incommensurability does not imply that rational comparability is impossible. On the contrary, with value-pluralism, alternatives can be "weakly comparable", without resorting to a single value (and to a single unit of measurement). Simon (1976) distinguishes between substantial rationality and procedural rationality. The former refers to the rationality of the result irrespectively of the way in which decisions are taken, while the latter refers to the rationality of the decision-making process itself. In deciding between weakly comparable alternatives, procedural rationality must substitute for substantial rationality (Martinez-Alier et al., 1998).

Where environmental management is characterized by conflicts in values and interests, it is very difficult to arrive at a straightforward and unambiguous solution. This implies that planning processes should be characterized by the search for acceptable compromise solutions through an adequate evaluation methodology (Munda et al., 1994).

Multi-criteria decision aid has proven to be a powerful tool to deal with complex environmental and energy management problems. Several examples can be found in Gamboa and Munda (2007), Diakoulaki *et al*. (2005), Barda *et al*. (1990), Georgopoulou *et al*. (1997), Cavallaro and Ciraolo (2005), Afgan and Carvalho (2002), Goumas and Lygerou (2000), Beccali *et al*. (2003), Haralambopoulos and Polatidis (2003), Sittaro (2010), and Janssen (1992). The objective of multi-criteria aid is not to discover some particular truth or an optimizing solution, but rather the final result should be seen as a creation (and not a discovery) aimed at facilitating "an actor taking part in a decision process to shape, and/or argue and/or transform his preferences, or to make decision in conformity with his goals" (Roy, 1990 p. 328).

From a practical point of view, one of the main advantages of multi-criteria decision aid is that it makes it possible to handle great amounts in a multi-dimensional way. It is a very transparent method because different valuations are not translated into a single numeraire (e.g. US$ or energy or exergy). Using data from scientific dimensions in their original units of measurement, it is also suitable for interdisciplinary approaches (Munda, 2008).

Of course, multi-criteria analysis cannot solve all conflicts but it can help decision making by shedding light on the nature of the conflict and on the way to find compromises, thus increasing the transparency of the decision-making process (Martinez-Alier et al., 1998). The most common use of multi-criteria analysis is in providing a final ranking of alternatives based on different criteria. In order to address

possible quality problems with data, a sensitivity analysis is often added. This work proposes a very different approach. A sensitivity analysis is included here mainly to give political weights to the different criteria reflecting diverging perspectives. The final rankings thus represent "politically sensitivity maps", to use Stirling's (1999) words.

The next section describes the methodological framework. Section 3 provides a historical-institutional analysis of the context of this study and includes a brief summary of the main social actors involved. Section 4 introduces the chosen alternatives and explains which criteria were used and how they were estimated. The results are included in section 5. The last section presents some final remarks on the overall process and on the specific results.

2. Methodological framework

A multi-criteria problem can typically be described by a finite set *A* of feasible alternatives a_1, a_2, … a_n (later called scenarios) and a family *G* of criteria g_1, g_2, ….g_m (representing the different points of view), by which alternatives are evaluated. Alternative a_1 is considered better than alternative a_2 if, according to the g_i criterion $g(a_1) > g(a_2)$.
Given the set *A* of alternatives and the set of criteria *G*, it is possible to build a *n x m* matrix whose elements report the performance of each alternative according to each criterion. Depending on the methodology used, the matrix can include quantitative, qualitative and also both types of evaluations (Munda, 1995; Munda et al., 1994).

The multi-criteria exercise can be summarized as follows (adapted from Gamboa, 2006; Gamboa and Munda, 2007):

- Problem structuring
    - Historical-institutional analysis
    - Identification of social actors
    - Definitions of preferences and aspirations
- Identification of alternatives
- Identification and estimation of criteria
- Selection and application of a ranking algorithm
- Analysis of results and sensitivity analysis

These phases are not intended to follow a chronological order. Rather, they influence each other dynamically. Once the results analysis has been performed, a new cycle can begin because the knowledge acquired may enable the social actors and analysts to change their perspectives and structure the initial problem in a different way.

The historical-institutional analysis is mainly aimed at defining the given problem by identifying social actors and eliciting their preferences and aspirations.

An analysis of the actors cannot be a simple enumeration of the agents involved. Important aspects to be included are the actors' main interests and stakes, the perception

of the problem, the degree of influence, and access to technical knowledge (Funtowicz et al., 1998). This phase of the research facilitates the generation of alternatives.

The institutional analysis in this research involved a review of various documents such as laws, policy documents, press releases and newspapers. This phase made it possible to identify the main actors. Subsequently semi-structured interviews (SSI) were held with exponents and representatives of the identified social actors (Appendix A1 reports a list of the interviews held). A question guide was previously prepared based on the information collected during the secondary data review. The main objective of the interviews was to gain knowledge on the perceptions, needs and aspirations of the social actors identified. In addition, following a snowball methodology, the interviews made it possible to identify other social actors.

As Roy (1985) specifies, the preference model used to evaluate the alternatives is not based on the alternatives themselves but on their consequences, which result from the alternatives and from the subjective evaluations of the social actors. The consequences are evaluated using certain criteria.

The choice of criteria is a technical translation of the social actors' desires and needs (Gamboa and Munda, 2007). Essentially, criteria represent the different points of view of the social actors, i.e. the axes along which the social actors argue, transform and justify their preferences. The comparisons obtained through these criteria should be considered as partial preferences because they are limited to the aspects taken into account by the point of view represented by the definition of each criterion (Bouyssou, 1990).

According to the multi-criteria problem reported above, in order to state that j is preferred to k (with j and k belonging to the set of N feasible alternatives), it is sufficient that $g_i(j) > g_i(k)$. This preference description represents a "true criterion". In this case, any difference between $g_i(j)$ and $g_i(k)$ implies a strict preference relation. However, even when the decision maker is a real person, their preferences are seldom clearly stated. Among areas of firm conviction may lie nebulous zones of uncertainty. Moreover, the data used to evaluate the performance of each alternative may be imprecise (Roy, 1990). This is why the introduction of discrimination thresholds is advisable. Here an indifference threshold is used, as depicted in Eq. 1 and 2.

$$j\,P\,k \Leftrightarrow g_m(j) > g_m(k) + q \qquad \text{(Eq. 1)}$$

$$j\,I\,k \Leftrightarrow |\, g_m(j) - g_m(k)\,| \leq q \qquad \text{(Eq. 2)}$$

where P represents a preference relation, I an indifference relation and q is the indifference threshold, i.e. the greatest value of the difference between the alternatives j and k which is not large enough to differentiate j from k on criterion g_m (Roy et al., 1986). The type of model in Eq. 1 and 2 is called "quasi-criterion".

From the chosen preference relations, a multi-criteria algorithm must be applied in order to derive the aggregate result. Given the context of this study, one important characteristic is that the result should not be an isolated alternative but a ranking[2]. Thus,

[2] Also called γ problem (Roy, 1990)

if the first alternative cannot be chosen because of political reasons (e.g. it gives rise to a strong conflict), other alternatives can be considered in their ranked order. In addition, it is important that the algorithm be non-compensatory so that a very good performance in one criterion cannot compensate for a bad one in an environmental criterion or vice versa. It is also advisable that the intensity of the preference information is not accounted for in order to avoid compensability. Weights should reflect importance coefficients and not trade-offs[3] (Munda, 2004; Vincke, 1992). Finally, it is essential that algorithm be simple and transparent. The Condorcet consistent rule developed by Munda (2005; 2009) has such properties. This is based on the maximum likelihood concept, that is, the maximum likelihood ranking supported by the maximum number of criteria for each pair-wise comparison, summed over pairs of alternatives. An *N x N* outranking matrix *E* can be built respecting the axioms of diversity (a complete order of alternatives can be obtained for each criterion), symmetry (only ordinal pair-wise information is accounted for, so intensity of preference is disregarded), and positive responsiveness (the degree of preference between alternative *j* and *k* is a strictly increasing function of the number of criteria and weights, which ranks *j* before *k*).

Any element of $E{:}e_{j,k}$ ($j \neq k$) is obtained by a pair-wise comparison between alternative *j* and *k* according to all *M* criteria. This pair-wise comparison is obtained by applying Eq. 3.

$$e_{jk} = \sum_{m=1}^{M} \left(w_m(P_{jk}) + \frac{1}{2} w_m(I_{jk}) \right) \qquad \text{(Eq. 3)}$$

where w_m is the weight for criterion *m*.

Let *T* be the set of all *N!* possible complete rankings of alternatives, and τ_s each individual ranking belonging to *T*. The score φ_s of each τ_s is obtained by the summation of e_{jk} over all the $\binom{N}{2}$ pairs *j, k* of alternatives (i.e. $\varphi_s = \sum e_{jk}$, where $j \neq k$, $s = 1,2,\ldots N!$ and $e_{jk} \in \tau_s$).

The final ranking τ^* is the one which maximizes φ_s (see Eq. 4):

$$\tau^* \Leftrightarrow \varphi_* = \max \sum e_{jk} \qquad \text{(Eq. 4)}$$

where $e_{jk} \in T$.

[3] Weights as trade-offs indicate how much a good performance in one criterion can compensate for a bad one in another (the analogy in economic jargon is the marginal rate of substitution). Weights as importance coefficients indicate how important a criterion is, but no compensation is implied.

3. Historical-institutional analysis

3.1 Historical context

Until the beginning of 1900 Mt. Amiata was a typical mountain area of volcanic origin where the main activities included agriculture, forestry and animal production, after which the mining for cinnabar radically changed the economic profile of the area. The mining sector grew so much that in 1965 it satisfied 35% of the world's mercury demand. Subsequently, a fast decline took place until 1976 when mines were closed down with hundreds of redundancies (Serafini and Sani, 2007).

Geothermal explorations started at the end of the 1950s with the installation of the first small plants in the municipality of Piancastagnaio to the east of the mountain and, in Bagnore (belonging to the municipality of Santa Fiora) in the west. Geothermal activity was soon perceived as an opportunity to counteract the economic depression caused by the end of the cinnabar mining. Government policies were set up to create new jobs. These included ornamental plant production in greenhouses benefiting from geothermal heat. These greenhouse areas were set up near Piancastagnaio, in an area named Casa del Corto.

ENEL, the once state-owned company operating and installing geothermal plants, was privatized at the beginning of the 1990s. During the same period a new plan called "Geotermia 2000" was launched to install 200 additional MW of capacity in Mt. Amiata (Bertini et al., 1995). It was around this plan that opposition to geothermal exploitation originated. At that time, the visual impact of the new plants was the main concern. In any case, three new plants were installed in Piancastagnaio and one in Bagnore (20MW each). Compared to the plants previously installed these new plants entailed the decoupling of installed capacity from on-site employment. This is because all plants are remotely controlled at a center a long distance away. As a consequence, the reduced employment effects of geothermal power plants became a main reason for discontent.

The municipality of Piancastagnaio asked various experts to contribute to the publication of a new book (1994) on the effects of geothermal exploitation. Some of the articles gave cause for concern among a small minority of the population. In the meantime the first reports on air quality released by the authority in charge of environmental control (called ARPAT) revealed that the emissions of the individual plants were much higher in Mt. Amiata than in the so-called traditional geothermal areas (further north, around Larderello).

In September 2000 two explosions occurred near Piancastagnaio because of geothermal fluid escaping from the soil. The inhabitants were evacuated and all the farm animals in the area died. These events gave rise to a new surge of opposition which included local rallies.

Another important element which caused concern among the population was the arsenic concentration in drinking water. In 2001 a decree set the limit of arsenic concentration at 10 μg/l. Since then, authorities have permitted expectation to the law regarding drinkable water. Given the high quantity of arsenic in the water, limits were

often raised to 20 or 30 μg/l. The problem was solved in 2009-2010 with the installation of arsenic abatement plants for drinkable water. However opponents to geothermal exploitation suspect that the high arsenic concentration may in some way be linked to the presence of the power plants.

At a regional level (i.e. within Tuscany in general), the growth of geothermal power plants was almost nil during the 2000s. In designing its new energy policy the regional government decided that the abundance of geothermal resources was an opportunity not to be wasted for the development of the renewable energies sector. In the energy plan approved in 2008 the installation of 200 MW[4] were planned. The regional government of Tuscany spearheaded an important negotiation with ENEL to set up a new compensation fund for the geographical areas where the geothermal plants are located. This gave rise to the so-called "general agreement on the exploitation of geothermal resources" signed in 2007 by all the municipalities of geothermal areas in Tuscany apart from the one in Mt. Amiata (i.e. Abbadia San Salvatore).

In addition to the final compensation, the general agreement included the acquisition of EMAS certification for all power plants, the commitment of ENEL to endorse new agreements with unions and industrial associations to enhance local employment and entrepreneurship, the promotion of scientific studies and research on the impact of geothermal exploitation, and the adoption of best available technologies.

3.2. The scientific debate

The scientific debate is mainly around two crucial issues: the effects of geothermal exploitation on water conservation and the effects on human health.

The main question on water regards the effects of geothermal exploitation on the quantitative and qualitative conservation of the potable aquifer. In order to introduce the reader into the geological context of this case study it is necessary to briefly describe the geothermal field of the Amiata volcanic complex (Southern Tuscany). There are two distinct water-dominated reservoirs: a so called shallow reservoir and a deep reservoir. The shallow reservoir is sited in the Mesozoic carbonatic formations at 500-1000 m depth. The deep one is hosted in the Paleozoic metamorphic basement at 2500-4000 m depth. These two reservoirs are separated by a low permeable layer and are considered part of a unique geothermal system[5] (Barelli et al., 2010). The shallow geothermal reservoir is overlain by cap rocks namely "Liguridi". Above them is located a layer of volcanic rocks or "Volcanites" which host the potable aquifer.

[4] The plan was for the whole Tuscan area (and does not specify where 200 MW are to be installed). So the 200MW target is not a target just for the Mt. Amiata area.

[5] Other characteristics of the geothermal reservoirs are: the shallow reservoir presents temperature ranging from 150 (in Bagnore) to 200°C while the temperature of the deep reservoir are more homogeneous and generally greater than 300°C (Bertini et al., 1995). In the deep reservoir the non condensable gas content is between 4% and 15% (Bertini et al., 1995) while in the shallow one is much higher: around 40% in Piancastagnaio and 85% in Bagnore (Barelli et al., 2010).

The effect of the geothermal exploitation on the conservation of the potable aquifer depends on various elements which, due to their complexity, are highly debated among the scientific community. It is worth remembering that the springs in Mt. Amiata are characterized by water shortages.

The first cartographic reconstruction of the potable aquifer can be found in a study by Calamai *et al.* (1970) who identified its piezometric level at 950 m.a.s.l. A geophysical survey carried out in 2003-2006 by the Italian National Research Council (CNR) identified an important depression in the phreatic aquifer[6] (Manzella, 2006). Finally the recent piezometer installed by the regional government revealed that the water table is at 780 m.a.s.l (thus suggesting a reduction of 170 m compared with the level identified in Calamai *et al.*).

This debate basically has two main positions. One position claims that the potable aquifer and the geothermal system are not connected; water shortages are mainly due to a reduction in rainfall, to the continuous drawings of water for drinking purposes from wells (many of which are illegal) and tunnels connected to waterworks, to the general crumbling conditions of the local waterworks and to the presence of the tunnels of the old mine. According to this position, the original reconstruction of the piezometric level of the phreatic aquifer of Calamai *et al.* is probably subject to errors due to the techniques used, to the few measurements taken and to the interpretations of the results. The depressions identified by the CNR study are also subject to the approximation typical of the technique used. In addition, the presence of contaminants in the water could be due to the natural presence of the same substances in the area and to the now closed mining activity. Different aspects of this view can be found in the EIA reports submitted by ENEL (2005, 2008, 2009a, 2009b, 2009c), in scientific articles by ENEL personnel, and in the study commissioned at the University of Siena (2008) by the Tuscany regional government. These studies find confirmation of their arguments in the prior works of Focacci *et al*. (1993), Barazzuoli *et al*. (2004) and Papalini (1989), among others.

The other position argues that the exploitation of geothermal power has provoked a depression in the geothermal reservoir and this depression has drawn water from the phreatic aquifer thus reducing the water table. The depression identified by the CNR study consequently indicates a recharge of the geothermal reservoir by the potable aquifer. Since the phreatic aquifer reduces its weight, the pressure that the water table causes on gasses coming from below also diminishes, consequently the ascent of contaminants from the geothermal reservoir is facilitated. In addition, the reduction in springs causes an increase in the concentration of poisoning contaminants. In summary geothermal exploitation can negatively impact the conservation of the potable aquifer. Different aspects of this view are held by Borgia (2007), by a study commissioned at EDRA by the regional government (EDRA, 2006a, 2006b), and by some geologists from the offices in charge of land protection and the prevention of hydraulic and hydrogeological risks of the regional government. A similar position can be found in

[6] The magnetotelluric method was applied for carrying out the geophysical survey.

older studies conducted by ENEL personnel with ENEL data (Burgassi et al., 1965; Calamai et al., 1970; Cataldi, 1965).

Just to give an idea of how the scientific debate is polarized, Borgia (2007) found a clear correlation between the vapor extracted for geothermal use and a reduction in the Mt. Amiata spring flows. However this correlation is completely negated in the study by the University of Siena[7]. Moreover, the legitimacy of the University of Siena study is contested by residence committees opposing geothermal exploitation because the study was conducted by a research team which included a member who was appointed by ENEL as an expert in previous civil suits.

The other main issue is the effect of geothermal exploitation on human health. A specific statistical-epidemiologic study (ARS, 2010) was conducted by comparing mortality and hospitalization statistics of the population in the geothermal areas with that of nearby and similar areas[8]. The results showed that considering the whole set of geothermal areas (i.e. including also the so-called traditional geothermal area), there was a small excess of mortality among males (+6%) with respect to the expected value and no excess of hospitalization. However, considering only the Mt. Amiata area, among males there was a significant excess of mortality (+13%), an excess of cancer (+19%), and an excess of mortality for breathing apparatus illnesses. While females presented an excess of mortality for acute breathing illnesses. Regarding hospitalization there were some excesses due to stomach cancer, breathing illnesses (only for females) and kidney failure. However, the study concluded that in all likelihood the excess of mortality and hospitalization was not due to the presence of geothermal plants because the most worrying indicators referred only to males[9] (and not to females who are exposed to the geothermal presence in the same way as males). According to the study, the excesses revealed were probably due to lifestyle and past employment, mainly mining. In spite of the reassuring conclusions, the results of the epidemiologic study remain a cause of concern and the regional government has recently agreed to finance further investigations.

3.3 Current status

Two mining concessions have been awarded to ENEL: one is to the east of Mt. Amiata (where Piancastagnaio and Abbadia S. Salvatore are located) and one is to the west (where Santa Fiora and Arcidosso are located)[10].

[7] The input data in the two studies was different.

[8] The analysis covered 2000-2006 for mortality statistics and 2002-2004 for hospitalization statistics.

[9] According to the study, the excess in breathing illnesses among females were consistent with regional trends.

[10] The mining concession of the West known as Bagnore, has an extension of 45.87 Km^2 and all the municipalities involved here belong to the Province of Grosseto. The mining concession of the east side is called Piancastagnaio, it extends over 47.91 Km^2 and all the municipalities belong to the province of Siena.

Four plants are currently operating in the east, all in the Piancastagnaio area. The characteristics of each plant are reported below with their official name (data are from the Environmental Impact Assessment submitted by ENEL, 2008, 2009b, 2009c):

- PC2. This is the oldest plant and currently has 8 MW of installed capacity. It was installed in 1969 and it is fuelled only by the shallow reservoir (which presents a very high quantity of non condensable gases with all their harmful elements). It is a dry steam power plant with no re-injection of fluid and no filters for air emission. This plant is responsible for the vast majority of the geothermal emissions due to geothermal exploitation of the area. The plant provides heat to the nursery activities of a nearby area called Casa del Corto, where greenhouses are located. These nurseries employ around 250 people.
- PC3. It has 20MW of installed capacity and was set up in 1990. It is fuelled only by the deep reservoir. It has a flesh steam technology[11], which partially re-injects the extracted geothermal fluid and is endowed with filters for the abatement of hydrogen sulphide (H_2S) and mercury (Hg) emissions (the filter is called AMIS). It is located in the south of Piancastagnaio.
- PC4 and PC5. These two plants are located near to each other in the north of Piancastagnaio. Each of the two plants has 20MW of installed capacity. PC4 was set up in 1991, and PC5 in 1996. The two plants are fuelled only by the deep reservoir. Their operation capacity is slightly lower than the theoretical capacity because of a lack of geothermal fluid. In order to operate at full capacity new wells need to be drilled. Without new wells the two plants reduce their power capacity every year. The two plants exploit flash steam technology with partial re-injection of the geothermal fluid and both are now equipped with the H_2S and Hg abatement filters.

A so-called "re-organization plan" for Piancasatgnaio mining license was submitted by ENEL and authorized by the regional government. This plan involves interventions only in Piancastagnaio. The main characteristics are: PC2 would be closed down, the heat that PC2 was providing to Casa del Corto would be provided by a new heat pipe connected to PC3, another heat pipe would be installed to provide the citizens of Piancastagnaio with heat, various wells would be drilled[12] to increase the production of existing power plants, and more than 16.3 km of various steam pipelines would be installed in order to connect the new wells with the power plants and to make the three plants part of a single system of steam distribution (details are from ENEL, 2008).

In the west of Mt. Amiata there is only one operating plant named Bagnore 3 (BG3 for short) from the name of the concession and the locality where the plant is

[11] A description of the technologies available for geothermal power plans can be found in Kagel *et al.* (2007), DiPippo (1991, 2005), and Bacci (1998) among others.

[12] Five new production wells would be drilled, two old wells would be reactivated, one old well would be deepened (all of them would be about 3,500 meters deep, thus reaching the deep reservoir). In addition, one new re-injection well of about 1,000 meters (up to the shallow reservoir) would be drilled (ENEL, 2005, 2009a).

located. It has 20MW of installed capacity with flash steam technology, partial re-injection of the extracted fluid and H_2S and Hg abatement filters. As mentioned the plant is located within the municipality of Santa Fiora.

A new project for the construction of a new 40 MW power plant (named BG4) in the west of Mt. Amiata was submitted by ENEL. Currently, the regional government has not yet authorized this new project.

3.4. Social actors

There are many stakeholders involved in the policy arena of this case and deciding which ones to include inevitably presents some degree of arbitrariness. The total list could include research organizations (the University of Siena, the University of Florence, a technical expert committee set up by the Regional government, and the National Research Council), the local association of hotels and the local association of service providers, environmental NGOs with a minor presence (e.g. Legambiente or Amici della Terra), a lawyers' NGO which assisted the resident associations during various legal actions, and also a Buddhist organization which attracts several followers in the west of Mt. Amiata. However, the social actors believed to have been the most active in recent years and/or which present a clear stake in the geothermal exploitation of Mt. Amiata are reported in Table 1.

Table 1: social actors

Social actor	Type	Description - Position
Tuscany Regional government	Regional government	The regional government has taken over the 20-20-20 EU objectives. According to the most recent energy plan, the Region should cover 39% of the electricity consumption (and 10% of thermal energy) with renewable energy sources by 2020 (Tuscany regional government, 2008). The additional amount of electricity that will have to be produced by all renewable energy sources is planned to be 3,542 GWh, of which 1,600 GWh by geothermal power. These objectives show the essential role that geothermal power is expected to have in order to achieve the desired targets. In addition, the regional government is in charge of authorizing the construction and operation of geothermal power plants.
ENEL	Private company	This is the sole company currently operating geothermal power plants in Italy (including on Mt. Amiata). Depending on the expected costs and revenues, it is interested in expanding the geothermal exploitation to produce more electricity and to be entitled to more green certificates (or to new incentive schemes).
Piancastagnaio municipality	Local authority	Four plants are located within its area with a total of 68MW of installed capacity. The municipality supports the re-organization proposed by ENEL in Piancastagnaio for several reasons: it involves the closing of PC2 which is a plant emitting high levels of air pollution; it entails the construction of a heat pipeline allowing inhabitants and companies to access low heat costs; it guarantees maximum capacity of electricity production and consequently the maximum level of royalties (which, to some extent, depend on the quantity of electricity produced).
Abbadia S. Salvatore municipality	Local authority	Part of the area is included in the mining concession awarded to ENEL for the exploitation to the east of Mt. Amiata. The municipality has never considered geothermal power as a driver of development and it opposes the construction of any new plants that would exploit high and medium enthalpy resources. Geothermal exploitation is perceived to be at odds with the development of the already important tourist sector. It is the only municipality in the geothermal area which did not sign the general agreement with ENEL and the Regional government, thus turning down the funds that this would have involved. In any case, it supports the re-organization plan because it means closing down PC2, so less air emissions would affect the municipality.
Santa Fiora municipality	Local authority	This is the local authority is on the west side of Mt. Amiata. A 20MW plant (called BG3) is located in its district. The new 40MW plant (called BG4) would also be located in the area, if installation is finally authorized. The municipality supports the presence of BG3 and the new construction of BG4. The main perceived benefit for the new plant is the possible development of small companies that could access low cost sources of heat. Royalties are also considered important. In fact, the vast majority of royalties are allocated to the municipality where the new plant is physically located.
Arcidosso municipality	Local authority	Part of the district is included in the mining concession awarded to ENEL for the exploration of the west side of Mt. Amiata however no plant is located in its area. Nevertheless, given the prevalent wind direction, the majority of air emissions from the BG3 (and BG4 if it is finally constructed) are deposited in its district (and not in the Santa Fiora area where the plant is located). The municipality is worried that the construction of BG4 would imply further emissions. It would tolerate its presence if the technical authorities guaranteed that the emissions will be maintained within acceptable levels and that the new plant would not interfere with the aquifer conservation.
Prospettiva	Residents	They are worried that exploitation of high enthalpy resources may provoke

Social actor	Type	Description - Position
Comune di Piancastagnaio	association with elected representatives in the city council	a geothermal fluid discharge (as has already occurred) and interfere with the conservation of the aquifer. They oppose the re-organization plan because it involves new wells and new pipelines, thus more exploitation of high enthalpy resources and a negative visual impact. They do not consider the closing of PC2 to be a positive element of the re-organization plan because dismissing PC2 should have been agreed independently from the plan. They ask for a moratorium of additional exploitations of the high enthalpy resources.
WWF	Environmental NGO	In the past they submitted a request for further integrations of the environmental impact assessment of BG4 regarding the effects of the planned plant on the ecological stability and on the food chains. They also submitted a formal claim to the European Union regarding the fact that the mining concession for BG3 was extended without an environmental impact assessment. They are worried about the additional emissions that BG4 would provoke and about the possible detrimental effects on the aquifer.
Rete Comitati di Difesa del Territorio	Regional network of associations	This is an network of associations committed to the natural and preservation of the area. It operates on a regional scale. They are worried that geothermal exploitation may deplete the water table, contaminate water resources with heavy metals, provoke superficial discharges of geothermal fluids, and cause dangerous emissions. They oppose the exploitation of high enthalpy resources. They also oppose the re-organization plan and the construction of the new plant in Bagnore.
Comitato per la Tutela dell'Ambiente Abbadia S.S	Residents' association with elected representatives in city council	This is a citizens association from the town of Abbadia San Salvatore. They fear that geothermal power plant emissions may affect human health. They are worried about the conservation of the aquifer and they believe the presence of geothermal power plants does not stimulate the economic development for the area. They oppose the exploitation of medium and high enthalpy resources.
Rifondazione Comunista Santa Fiora	Local branch of a left-wing party	It is the local branch of a political leftist party. It represents the opposition to the development of geothermal power in the small town of Santa Fiora. Members are mainly worried about the environmental impact that the construction of the new plant in Bagnore (BG4) would involve. They oppose the construction of BG4 because it implies a three times larger capacity (in Santa Fiora area) with the same technology of BG3.

4. The multi-criteria matrix

The multi-criteria methodology entails identifying a set of alternatives and a set of criteria to compare such alternatives.

4.1 Generation of alternatives

The scenarios taken into consideration are seven with four overall origins: 1) the preservation of the status quo 2) the projects planned by ENEL, 3) scenarios generated after in-depth discussions with technical experts and scientists from the geothermal sector in order to address (at least partially) the worries of some of the social actors 4) the formulation in "scenario terms" of the requests of the opponents to the ENEL projects.

The scenarios considered are:

A. BaU (Business as Usual). This scenario means maintaining the current conditions. All five plants remain operating as they are. At the same time, two plants in Piancastagnaio (PC4 and PC5) experience a reduction in their production capacity because of a lack of geothermal fluid.
B. Reorg (reorganization). This plan is proposed by ENEL and has already been authorized. The details are reported in section 3.3.
C. ClosingPC2. This scenario envisages that PC2 would be closed down and a new heat pipe would be installed from PC3 in order to provide the Casa del Corto area with heat (as in the previous case). No other interventions are envisaged, so the annual electricity production of PC4 and PC5 would decrease.
D. Reorg+BG4. This scenario joins the two projects proposed by ENEL. In Piancastagnaio a re-organization is planned exactly as explained in B. To the west of the mountain a new plant of 40MW capacity (BG4 for short) would be installed with flash steam technology beside the existing plant (the total installed capacity in Mt. Amiata would be increased from the current 88MW to 120 MW). In addition to the installation of a power system (which in this case involves cooling towers with six cells and the H_2S and Hg abatement filters), the construction of the new plant entails drilling new wells[13] and the installation of about 12 km of steam pipelines.
E. Reorg+40CC. As in the previous case this scenario involves the re-organization plan proposed by ENEL in Piancastagnaio. The new power plant to be constructed in Bagnore would have a closed cycle technology. This means that the fluid extracted from the geothermal reservoir would be totally re-injected (and not partially as normally happens with traditional flash steam technology).

[13] Six new wells would be drilled and two old wells would be re-activated (all of which would reach the deep reservoir and would be used for production purposes). In addition, two new wells reaching the shallow reservoir would be drilled for re-injection purposes.

The only technology presenting this characteristic and already on the market is binary cycles [14], which is the technology envisaged here [15]. The construction of this new plant with 40MW of installed capacity would mean using a wider area and a higher cooling towers than in the traditional flash stem technology (because of the different cooling systems), along with a higher number of wells to be drilled in order to totally re-inject the extracted fluid.

F. ClosingPC2+20CC. This scenario envisages that the PC2 plant would close down and that a new heat pipe would be installed to provide Casa del Corto area with heat. In Piancastagnaio no further interventions would be made. In addition, a new plant with 20MW of installed capacity and closed cycle would be built in Bagnore. As in the previous case the technology would be binary cycles. Obviously, the area occupied by this new plant would be smaller than in the previous case (but much larger than traditional plants based on flash steam technology).
G. Reorg+20CC. In Piancastagnaio the re-organization plan would take place exactly as in B. In addition, a new 20MW plant with a binary cycle technology would be installed in Bagnore.

Each scenario is assumed to have a 30-year duration period.

4.2. Choice and estimation of criteria

Eleven criteria were taken into consideration representing the results of the institutional analysis described in Section 3: 1) electricity produced, 2) profitability of the plants, 3) municipality revenues, 4) direct heat use, 5) greenhouse gas (GHGs) emissions avoided, 6) H_2S emissions, 7) Hg emissions 8) ammonia (NH_3) emissions, 9) arsenic (As) emissions, 10) possible impact on the phreatic aquifer 11) visual impact. Initially it was considered also direct employment among the set of criteria. However, it was excluded because the local actors never actually mentioned it in the interviews. The plants are controlled remotely at a control centre a long distance away. In Mt. Amiata there are few locals employed in maintenance. In addition, the number of local employees would not be significantly different in the considered scenarios. Of course, during a plant's construction, the employment effect can be important. However, this effect would be

[14] With binary cycles, the geothermal water heats another liquid. The two liquids are kept completely separate through the use of a heat exchanger used to transfer the heat energy from the geothermal water to the working fluid. The secondary fluid vaporizes into gaseous vapor and turns the turbines that power the generators. With air cooling the geothermal fluids never make contact with the atmosphere before they are pumped back into the underground geothermal reservoir (Kagel et al., 2007). ENEL itself installed two binary cycles plants in Nevada amounting to 65Mw of total capacity and has acquired rights to install 150 MW of additional capacity in different USA states (Roxborough, 2010)

[15] Theoretically a closed cycle can also be obtained with total re-injection and flash steam technology. In Iceland there are plans to install this type of prototypal plant, but there are no operating and commercial cases at the moment of writing. Consequently, it was decided not to consider this possibility in this work.

limited just to a few years and the majority of employees and companies contracted for the construction of the plant would not be from Mt. Amiata. Moreover, the employment effect of the construction phase could only be estimated with a very high degree of approximation. The potential of new companies accessing low cost heat sources may have some positive employment effect. However, such an effect is already reflected in criterion 4. Some studies also include social acceptability among the criteria (Beccali et al., 2003; Cavallaro and Ciraolo, 2005; Chatzimouratidis and Pilavachi, 2008; Liposcak et al., 2006). However social acceptability is probably a consequence of the evaluation of other criteria.

The criteria taken into consideration are reported below along with the way they were estimated.

Criterion 1: Electricity produced

This criterion reflects the point of view of the regional government. In fact, Tuscany is required to reach specific electricity targets produced from renewable resources. Of course, this criterion is also of interest for the plant operator because the electricity produced is sold on the market.

The amount of electricity produced by each plant was extracted from the a regional government database (2011).

In the scenarios that do not include the reorganization plan, the electricity production of PC4 and PC5 diminishes over time. This is clearly evident from the time series extracted from the abovementioned database. The average annual change rates of electricity production were calculated for each plant. These rates were used to estimate the annual amount of electricity produced by each plant for the duration of the scenarios. It was also assumed that once a power plant produces just 40% of its net capacity the plant is closed down (DiPippo, 2005). This is the case of PC4 in BaU, in Closing PC2 and in Closing PC2+20CC. It was also assumed that once PC4 closes down, all the geothermal fluid which was originally used by PC4 is directed towards PC5, which returns to full capacity (this is because the wells connected to PC4 and PC5 are part of the same pipeline system). As previously mentioned all the scenarios excluding BaU involve PC2 closing down, thus no electricity would be produced by this plant.

For the scenarios that include the re-organization plan and for all new plants, the annual electricity production is estimated by multiplying the net capacity of each plant by 8,000 hours[16].

The net capacity of a traditional flash steam power plant is 95% of the gross capacity. With binary cycle technology, the thermodynamic losses are much higher and on average the net capacity is 77% of the gross capacity[17].

As previously mentioned, in all scenarios where the reorganization plan is not included, some power plants would slightly reduce their electricity production. When a criterion varies over time (or in space) a “point-reduction” is needed to sum up a given

[16] This is the average yearly duration of working hours of each plant as indicated in the EIA report for BG4.

[17] Personal communication from ENEL Ricerche

distribution by a single value (Roy, 1985). In this work the median value of the annual electricity production was used. The results for each scenario are reported in Table 2.

Table 2: Electricity production (MWh)

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
531,670	620,800	504,670	924,800	867,200	577,350	744,000

Criterion 2: Company profitability

This reflects the point of view of the company operating and installing the power plants. The profitability is measured by the net present value (NPV) of each scenario.

The main sources of revenue are the electricity produced and the incentive scheme. The price of electricity was obtained by means of a weighted average of the price of electricity exchanged in the electricity market managed by the company in charge (GME, 2011) from 2005 to 2010. The current incentive scheme for geothermal power plants is the green certificate (GC), that is, a market-based mechanism. The GC market in Italy is characterized by an excess of supply (GSE, 2011) so the withdrawal price set by law was chosen as the reference price. During the period when this research was carried out, a new law was introduced, radically changing the incentive system. Basically, from 2011 to 2015 the GC system is maintained as is and the withdrawal price is set at 78% of the price at which the GCs are placed[18] by the company in charge of allocating incentives for renewable energies (i.e. GSE). Thus the assumed prices are 72.32 €/MWh for the electricity and 88.22 €/MWh[19] for the GCs until 2015. The price of the GCs is certainly not the price that would be revealed if the withdrawal mechanisms were not in place. In fact, the rationale for a withdrawal price system is to avoid a too low price because of the excess supply of GCs. Consequently, once the withdrawal system is not in place, the price of the GCs (or of their substitute) is expected to be much lower. The recently introduced law establishes that after 2015, the GC system will be substituted by an auction system. The price resulting from the auction system was assumed to be 45€/MWh. This is the price simulated by REF (2011) through the GreeCe model in the absence of a withdrawal price for the GCs. Of course such an estimation may easily be wrong. Therefore a robustness analysis is needed.

Investment, maintenance and operational costs were taken from various sources (Bertani, 2009; Entingh and McVeigh, 2003; Hance, 2005; Petty, 2005; Sanyal, 2004), updated and adapted to the Italian case under the supervision of a geothermal plant expert.

[18] Such a price is set by law as the difference between 180 €/MWh and the reference price of the previous year for renewable energies set by the relevant government authority. In 2011 this price was 113.1 €/MWh.

[19] This value must be multiplied by a given coefficient, which depends on the type of renewable source from which the electricity is produced. The coefficient for the electricity produced by geothermal energy is 0.9

In order to take into account the entrepreneurial risk in choosing the discount rate, We decided to increase the interest rate by 3%[20] earned by the government bonds expiring in 30 years (i.e. the entire duration of each scenario). The resulting discount rate is 10%. Table 3 reports the NPV of the seven scenarios and includes the effects of different GCs values.

Table 3: Profitability (NPV in thousands €)

GC(€/MWh)	BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
45.00	177,150	239,380	171,993	294,782	236,487	159,475	231,459
66.61	177,150	247,476	171,993	324,826	262,219	168,698	248,778
88.22	177,150	255,572	171,993	354,868	287,949	177,920	266,095

Criterion 3: Municipality revenues

This reflects the point of view of the town councils. For each municipality the revenues generated by geothermal activities consist of the following:

a. 0.13 cents per KWh produced. At least 60% of this sum is for the municipality where the plant is located and the remaining part is proportionally distributed to the municipalities according to the mining license area of each municipality.
b. The compensation fund in the general agreement on the exploitation of geothermal resources.
c. The real property tax. According to the interviews with the mayors, in Piancastagnaio this amounted to about €50,000 and in Santa Fiora to €3,000.

Abbadia S. Salvatore is the only municipality which did not sign the general agreement on the exploitation of geothermal resources. Consequently this municipality benefits only from the revenues in point *a*.

The annual flow of revenues is actualized though its NPV. There is no reason why the municipalities representing local communities should prefer higher gains (or lower costs) today than tomorrow. Consequently, the discount rate was chosen to be equal to the inflation rate: 3%. The results are reported in Table 4.

Table 4: NPV of the municipality revenues (NPV in thousands of Euros)

	BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
Santa Fiora	10,907	10,907	1,287	38,784	34,647	23,644	23,655
Arcidosso	6,074	6,074	7,317	19,095	18,086	12,073	12,084
Piancastagnaio	14,781	32,054	18,759	32,085	27,914	17,522	27,818
Abbadia S.S	1,994	3,278	4,208	7,322	7,322	4,208	7,322
Total	33,755	52,312	31,570	97,286	87,970	57,447	70,879

[20] Auction held on 14 February 2011

Criterion 4: Direct heat uses

The possibility to access a low cost heat source arose several times during the interviews. Direct heat use is considered important both for house heating and for small industrial activities. In Tuscany the main energy source for house heating is natural gas which is distributed though pipelines. However, one of the four villages - Piancastagnaio - is not connected to a natural gas network, so houses are heated using GPL and diesel boilers or through electric systems. Consequently heating is more expensive than in the rest of the region. In addition, even in the areas that are connected to a natural gas network, it is believed that access to low cost heating would make local companies more competitive and would encourage new companies to be set up. This is believed to be very important to limit the emigration flow due to the few employment opportunities available in the area.

Geothermal power plants can provide a low cost source of heat by selling the excess heat which is not used in the plant (e.g. after the steam resulting from the geothermal fluid has fuelled the turbine).

The availability of heat from geothermal power plants is evaluated in linguistic terms. Following the approach used by Roy and Silhol (1986), the qualitative evaluation was translated into a quantitative scale, which is reported below in Table 5. Since the scale reports increases for worse performances, the desired direction is *decrease*.

Table 5: Qualitative evaluation of direct heat uses

Evaluation	Perfect	Very good	Good	More or less good	Moderate	More or less bad	Bad	Very bad	Extremely bad
Scale	1	2	3	4	5	6	7	8	9

Heat availability essentially depends on the size of the new plants (the larger the size, the more excess heat is available), on the technology used (binary cycle plants are less efficient in producing electricity than flash steam power plants, so they present a higher quantity of excess heat) and on the specific arrangements offered by the plant operators. In this regard, the aforementioned reorganization plan involves the construction of a new heat pipeline to provide Piancastagnaio with heat.

The small town of Santa Fiora is already provided with heat from BG4. Thus a direct heat use is already an option for a very small part of the whole Amiata area. The BaU and ClosingPC2 scenarios envisage that direct heat use is maintained at the current level (which benefits only Santa Fiora), so the Piancastagnaio area would still need the high cost heating systems that it is using now. The evaluation is considered “more or less bad”. Closing PC2+20CC means that more excess heat is available for the west side of the mountain (where heating from the geothermal plant is already available) in comparison with the current level. An evaluation of this scenario is therefore obtained by a one step increase in the scale to the level of “Moderate”. As already mentioned, Reorg entails the construction of a new pipeline for heating Piancastagnaio (which is not connected to the natural gas network), which means that this scenario is considered

"more or less good". In addition to the new pipeline in Piancastagnaio, Reorg+BG4 and Reorg+20CC envisage the construction of a new plant in the west, thus the evaluation for these two scenarios is a step further: "good". As the above scenarios Reorg+40CC entails installing a pipeline in Piancastagnaio and also envisages the construction of the largest plant with the highest excess supply, the evaluation is "very good".

The evaluation of each scenario is reported in Table 6.

Table 6: Direct heat use

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
More or less bad	More or less good	More or less bad	Good	Very good	Moderate	Good

Criterion 5: GHG emissions avoided

This criterion is of interest for the regional government. In fact the regional government took over the EU 20-20-20 target,[21] and the production of electricity from renewable energy is part of the GHG abatement strategy. Geothermal power plants can emit a large amount of GHGs in the form of CO_2 and CH_4 and their exact value depends on the specific composition of geothermal fluid. However their emissions are not included in the quotas allocated to EU countries. Therefore the amount of GHGs emitted from geothermal power plants is not part of the amount of GHGs that Italy and Tuscany need to reduce[22]. Thus, the GHG emissions caused by geothermal power plants are not accounted for in this study.

The amount of electricity produced in Tuscany from each fossil fuel source was derived from Terna (2010) and from the Tuscany regional government (2009). In 2008 the electricity production obtained from fuel oil was 13%, while the rest was obtained from natural gas. An amount of 557.1 Kg of CO_2eq is avoided for geothermal MWh. This value was calculated using data from the regional government 's database (providing data from individual power plants) which shows that the average emissions of CO_2eq per MWh produced by fuel oil is 763.2 Kg and 526.2 Kg by natural gas. It was then assumed that the electricity obtained by the geothermal power plants replaces the electricity produced by burning fuel oil and natural gas in the same proportion as such plants contribute to the total quantity of electricity produced by fossil fuels.

The median value of the annual GHG emissions avoided for each scenario is shown in Table 7.

[21] The 20-20-20 are two main targets to be achieved by the EU by 2020: at least 20% of GHGs reduction in comparison to the 1990 emissions and at least 20% of energy consumptions must be obtained by renewable energy. On 22 June 2011 the European commission also proposed a new directive to achieve an increase of at least 20% in energy saving compared to the PRIMES 2007 baseline.

[22] This is because it is generally assumed that the GHG emissions from geothermal power plants would naturally occur in a diffused way, so geothermal power plants would be simply concentrating emissions they cannot be held responsible for.

Table 7: Tons of CO_2eq emissions avoided

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
296,187	345,840	281,145	515,194	483,106	281,145	414,473

Criteria 6, 7, 8, 9: H_2S, Hg, NH_3 and As emissions

The emissions can be a cause for concern for the various social actors involved in the study (municipalities, the regional government, ENEL, etc) however, they represent the greatest worry for residents.

These criteria include the emissions that are discharged in the highest amounts, and which are considered most dangerous, namely H_2S, Hg, NH_3, and As[23].

H_2S produces an unpleasant smell at low levels of concentration (but its perception diminishes with prolonged exposition), and beyond certain levels it represents a serious hazard for human health. Hg, NH_3 and As can also represent a health problem beyond certain concentration levels[24]. The last ARPAT report on the emissions of geothermal power plants shows that although the concentration value of the WHO guidelines for health protection in the 1997-2009 measurement period was occasionally exceeded, the concentration of H_2S and Hg in Mt. Amiata is much higher than in the traditional geothermal area.

It is worth mentioning that H_2S and NH_3 contribute to the formation of inorganic secondary particulate matter (PM) whose effects are on a regional scale. In this regard the regional government has specific objectives for PM reduction.

From a comparison of the geothermal areas in Tuscany, the total Hg emissions flow in Mt. Amiata is much higher than in other areas (Tuscany regional government, 2010). In addition, ARPAT (2010) reports a frequent overflow of the maximum Hg and NH_3 flow allowed by law among plants (but the regulation is still respected because the maximum concentration limits are not exceeded)[25].

NH_3 emissions from geothermal power plants are especially important in Tuscany because they represent the second source of NH_3 emission after agriculture, amounting to 30-40% of the total emissions of this substance (Tuscany regional government, 2010).

Many different variables should be taken into consideration to estimate the concentrations of emissions in the air (such as wind speed and direction, temperature and rainfall) and a specific model should be used. This is certainly very important but goes beyond the scope of this study. Consequently, only the annual quantities of air emissions are calculated and not air concentrations.

[23] Others could have been included such as antimony, methane, and boric acid, however according to the literature consulted, given their emissions levels, they are not thought to represent a problem.

[24] The maximum concentration of the polluting elements of the WHO guidelines and other authorities for health protection are reported in ARPAT (2010), Tuscany regional government (2010) and Bacci (1998).

[25] The regulation on geothermal power emissions set a first maximum limit on the flow and a second limit on the maximum concentration of the polluting substance. Only when the first limit is not respected, does the second take place. Thus, when the maximum flow limit is exceeded, the regulation is still respected if pollutant concentration does not exceed the level indicated by the second limit.

The emission factors indicating the amount of emissions per MWh were calculated by averaging the individual ARPAT (2010)[26] emission measurements. The ARPAT database reports the emissions both in the presence and absence of AMIS. The environmental impact assessment (EIA) report for BG4 specifies that on average the abatement filters for H_2S and Hg (called AMIS) work 90% of the time. Consequently the emission factors were calculated as a weighted average emission in the presence and absence of AMIS. In order to calculate the annual emissions, the resulting emission factors were multiplied by 8,000, which is the number of hours a power plant normally works (ENEL, 2005). For the remaining 760 hours the plant is assumed not to work due to maintenance. When the power plant is not working, the flow of the wells is reduced to about 50% of its working flow, and wells discharge directly into open air, that is, without AMIS and without re-injection of the fluid (at plant level). Thus the emissions during the maintenance period were estimated as the emissions that would occur without AMIS, with 50% of flow and increased by the quantity normally re-injected. The quantity normally re-injected was assumed to be 25% of the flow that reaches the plant[27] (ENEL, 2005).

Tables 8, 9, 10 and 11 report the median annual values of H_2S, Hg, NH_3 and As emissions for each scenario.

Table 8: H_2S emissions (Tons/yr)

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
1,825	1,070	1,015	1,727	1,119	966	1,021

Table 9: Hg emissions (Kg/yr)

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
605	309	251	391	317	244	302

Table 10: NH_3 emissions (Tons/yr)

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
3.088	3.392	2.929	7.827	3.530	2.792	3.255

Table 11: As emissions (kg/yr)

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
16	19	15	26	19	15	18

[26] In the PC4 plant the AMIS system was only installed recently and no measurements were available. The abatement efficiency was thus estimated by averaging the efficiency of the same filters on all the other plants in Mt. Amiata.

[27] Even though the quantity to be re-injected was taken from an ENEL source, it should be noted that it represents an approximation and the actual level could change according to different levels of condensation.

Criterion 10: Impact on the aquifer

The evaluation of this criterion is unavoidably subject to strong uncertainty. The heated scientific debate mentioned in Section 3.2 is also a result of this uncertainty.

Given the uncertainty underlying the effects of geothermal exploitation on the conservation of the water aquifer and the critical importance of this issue (the aquifer provides water to more than 700,000 people), a a precautionary principle is here proposed. Consequently it is assumed that geothermal exploitation may affect the conservation of the aquifer[28]. Therefore if the extraction of vapor from a geothermal reservoir can cause a depression, which draws water from the potable aquifer, the consequence is that the less vapor is extracted, the better it is for the conservation of the potable aquifer.

The quantities of extracted vapor in the different scenarios was estimated from the EIA data (ENEL, 2005, 2009c) and are reported in Table 12. With binary cycle plants all extracted fluid is assumed to be re-injected.

Table 12: net quantity of extracted fluid (T/h)

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
284	194	164	280	194	164	194

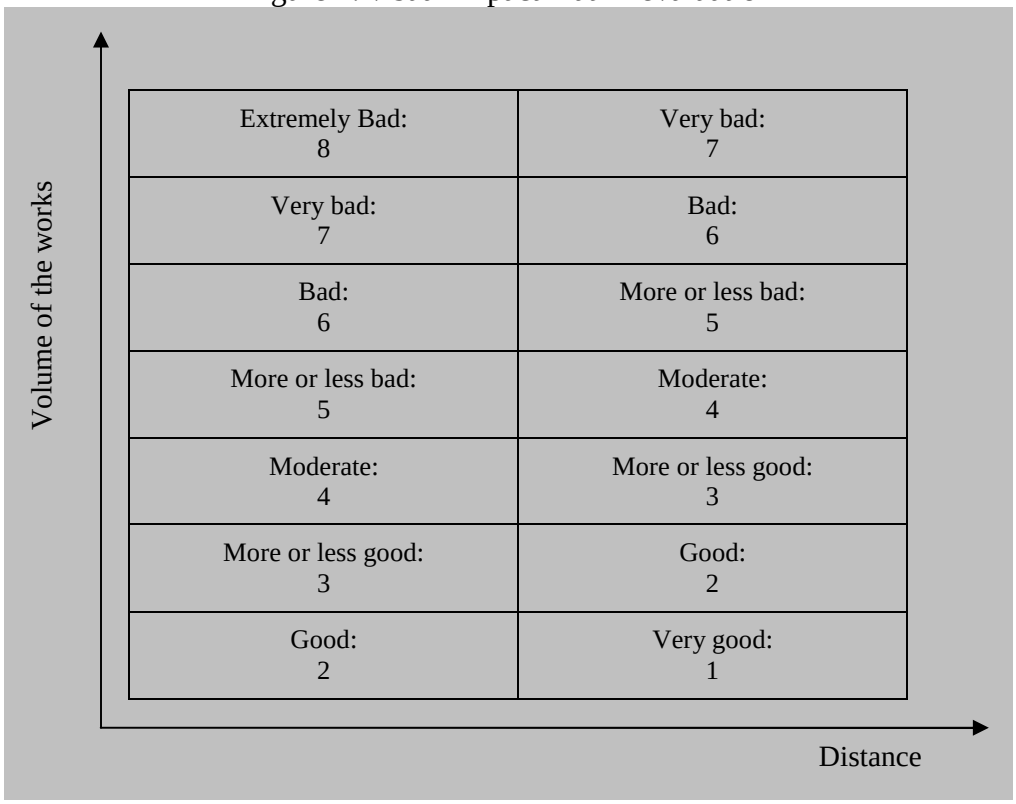
Criterion 11: Visual impact

There are many tools for assessing the visual impact of a project, however given the scope of this study no sophisticated techniques were used. Similarly to the approach proposed in Munda *et al*. (2006), a matrix aimed at facilitating the evaluation of the visual impact was built with two axes: distance of the additional work from the main villages of the area (Piancastagnaio in the east and Santa Fiore in the west) and the volume of the site of the power plants (see Fig 2). Thus the higher the distance and the reduced the visibility of the location, the better the visual impact. The visual impact would naturally be evaluated though a qualitative judgment. As for criterion 4, the qualitative evaluation was translated into a quantitative scale, which is reported in Figure 2. The result is that the higher values of the scale mean a worse visual impact, so lower values are preferred to higher values.

The visual impact of the BaU scenario is considered as being “moderate”. So the additional work of the other scenarios involves changes in the visual impact evaluation with respect to the “moderate” level of the BaU scenario.

[28] A similar view is assumed in the advice on the re-organization plan of Piancastagnaio provided by the three watershed authorities (Tevere, Ombrone and Fiora), the office in charge of the water resources protection and management and by the office in charge of the prevention of hydraulic and hydro-geologic risks of the regional government. The document concludes that it is not possible to rule out that the vapor extraction cannot provoke an important impact on the phreatic aquifer.

Figure 2: visual impact matrix evaluation



On the basis of the above considerations, the visual impact of the different scenarios is reported in Table 13.

Table 13: visual impact

BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2+20CC	Reorg+20CC
Moderate	More or less bad	Moderate	Bad	Very bad	More or less bad	Bad

5. Ranking alternatives

In this work the decision maker is not a real person whose preferences can be elicited in some way. Consequently the model only represents a system of preferences aimed at answering certain questions (Roy, 1991).

A choice must be made about weights. These reflect the importance of a given criterion with respect to the others. Different techniques can be used[29] but in the context of this work with no individual decision maker, it is impossible to establish a set of weights to satisfy all the social actors. Some models like ELECTRE IV (Roy and Hugonnard, 1982) and NAIADE (Munda, 1995) simply avoid assigning weights to criteria. However these models do assign weights in an implicit way. In fact, if no weights are assigned, the result is that all criteria have the same weight. As previously stated, one of the main advantages of a multi-criteria analysis is its inherent transparency. If criteria are assumed to have the same importance, it is advisable that all criteria are assigned an equal weight in an explicit way.

Another approach suggested by Munda (2008) consists in assigning each criterion to one of the three dimensions of the sustainability concept (economic, social and environmental). The weights are allocated to criteria proportionally so that each dimension has an equal weight. Such an approach is certainly defensible from a theoretical point of view. However, its main problem is that often criteria can be assigned to the three different dimensions only with a very high degree of arbitrariness. For instance, considering the criteria used in this study, the profitability of the plant would certainly be considered as being 'economic', but what about electricity production? Is it economic (because it is sold on the market), social (because it is used by humans), or environmental (because it comes from a renewable energy source)? The same would apply to direct heat use. And what about polluting substances? Are they environmental because they affect the environment, or social because they can also affect human health?

This work does not claim to provide a complete answer to the conflict described, but rather to explore the problem from different points of view. A sensitivity analysis applied to relative weights is thus an extremely powerful technique.

Here a final ranking is presented assuming equal weights of all the criteria, and further results are explored by changing the relative weights of criteria.

Table 14 represents the multi-criteria impact matrix derived by joining the evaluation vectors of the previous section. Table 15 reports the outranking matrix by applying Eq. 3 with equal weights and the indifference threshold indicated in Table 14.

The choice of threshold value is very often based on common sense. In addition, it nearly always contains a certain amount of arbitrariness (Roy et al., 1986). Yet, in many situations, any reasonable value of the indifference thresholds other than zero, leads to a model of preference that seems more convincing than equating the indifference threshold to zero (Bouyssou, 1990).

In this research project, indifference thresholds were set using two common sense approaches. When an external benchmark was available, the indifference thresholds were set as a minimum percentage of achievement of the objectives reflected by the selected criteria. This was the case for *electricity produced* and *GHGs avoided*. These

[29] See Edwards (1977) for SMART, Edwards and Barron (1994) for SMARTER, Jia *et al* (1998) for SWING, Simos (1990) and its amendments (Figueira and Roy, 2002) and Wang *et al*. (2008) for pair-wise comparison techniques

two criteria are mainly of interest to the regional government. In fact, the regional government has specific objectives for electricity production from geothermal power and GHG reduction. Thus, the threshold values reflect minimum percentages of achievements of the regional government's stated objectives. When an external benchmark was not available, the thresholds were set as the minimum percentage of current levels. This is the case for all criteria except *electricity produced* and *GHGs avoided*. In any case, a robustness analysis is included to verify that arbitrariness does not significantly affect the final results.

Table 14: multi-criteria impact matrix

Criteria	Dir.	BaU	Reorg	ClosingPC2	Reorg +BG4	Reorg +40CC	ClosingPC2 +20CC	Reorg +20CC	Threshold value
Electricity prod.	↑	531,670	620,800	504,670	924,800	867,200	577,350	744,000	100,000
Profitability	↑	177,150	239,380	171,993	294,782	236,487	159,475	231,459	15,000
Municipalities rev.	↑	33,755	52,312	31,570	97,286	87,970	57,447	70,879	5,000
Direct heat uses	↓	6	4	6	3	2	5	3	-
Avoided GHGs em,	↑	296,187	345,840	281,145	515,194	483,106	281,145	414,473	150,000
H_2S emissions	↓	1,825	1,070	1,015	1,727	1,119	966	1,021	250
Hg emissions	↓	605	309	251	391	317	244	302	50
NH_3 emissions	↓	3,088	3,392	2,929	7,827	3,530	2,792	3,255	500
As emissions	↓	16	19	15	26	19	15	18	3
Impact on aquifer	↓	284	194	164	280	194	164	194	50
Visual impact	↓	4	5	4	6	7	5	6	-

Table 15: outranking matrix

	BaU	Reorg	ClosingPC2	Reorg+BG4	Reorg+40CC	ClosingPC2 +20CC	Reorg+20CC
BaU	0	0.2727	0.4545	0.3636	0.1818	0.3636	0.2273
Reorg	0.7273	0	0.5455	0.5455	0.4091	0.4545	0.4091
ClosingPC2	0.7273	0.4545	0	0.5455	0.4545	0.4545	0.4545
Reorg+BG4	0.6364	0.4545	0.4545	0	0.3636	0.4545	0.5000
Reorg+40CC	0.8182	0.5909	0.5455	0.6364	0	0.5455	0.5909
ClosingPC2+20CC	0.6364	0.6364	0.5455	0.5455	0.4545	0	0.4545
Reorg+20CC	0.7727	0.5909	0.5455	0.6818	0.4091	0.5455	0

One disadvantage of the aggregation procedure applied here is that there can be more than one ranking with the same maximum likelihood ranking τ^*. This is why the results presented in the following tables include more than one ranking. The rankings presenting the highest score when equal weights are applied are reported in Table 16. It is worth noting that equal weight methods are the most common approach in renewable energy analyses (Wang et al., 2009).

Table 16: ranking for equal weights among all criteria

1°	2°	3°	4°	5°	6°	7°
Reorg+Bin40	Reorg+Bin20	Bin20	Reorg	ClosingPC2	Reorg+BG4	BaU

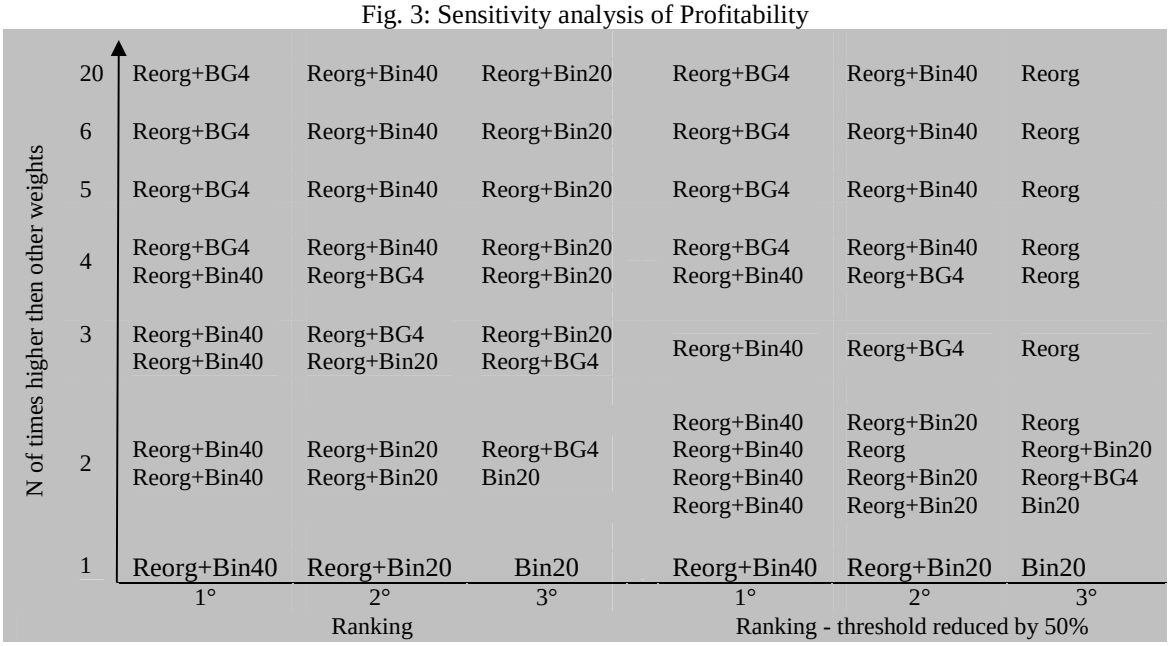
Some interesting results can be observed. The current scenario is the worst. In this sense, the discontent that geothermal power has generated can be justified. Also, with equal weights, the scenario joining the two ENEL proposals (i.e. Reor+BG4) is the second worst.

Scenarios including binary cycles technologies score between best positions. In fact, Reorg+Bin40 ranks first. However, as explained in the institutional analysis section, the reorganization plan (included in Reor+Bin40 and in Reorg+Bin20) would be strongly opposed by the Prospettiva Comune di Piancastagnaio and Comitati di Difesa del Territorio. Bin20 does not score as well as Reorg+Bin40 but might receive less social opposition.

A sensitivity analysis was applied to evaluate how rankings change by varying the relative weights of criteria. A robustness analysis was also applied to the indifference thresholds. Of course, an extremely high number of sensitivity analyses are possible by combining all possible weights of each criterion with the other weights of all the other criteria and with all possible values of the indifference thresholds. Limits need to be set. It was decided to limit the possible number of sensitivity analyses to the following possible combinations: an increase in the weight of each criterion by one and maintaining all other weights at their original value of one (all weights are normalized to make a total of one), increase the threshold value of the same criterion by 50%, reduce the threshold value of the same criterion by 50%, and increase the weights of two criteria that reflect a specific point of view. The most significant changes that were observed by increasing or reducing the indifference thresholds are included in the tables. When the different values of the indifference thresholds do not cause significant changes in the rankings, the robustness analysis of the indifference threshold is not reported. Only the most interesting results obtained by the sensitivity analysis are reported here.

The profitability criterion is mainly of concern for ENEL. The results obtained by changing the value of its weight are in Fig. 3 (for reasons of space, just the three best positions are included).

Fig. 3: Sensitivity analysis of Profitability



The position of Reorg+BG4, i.e. the projects proposed by ENEL, improves by increasing the weight of the profitability criterion. However, Reog+Bin40 keeps scoring very well. Figure 3 does not report the tails of the ranking. These would show that if the profitability weight is five, Bin20 is in last position. This results suggest that with increasing importance for this criterion, Bin20 would probably be rejected by ENEL unless it is subsidized.

Figure 4 shows different rankings obtained by increasing the weight of the Electricity Production. Reorg+Bin40 remains in first position even with a high weight. Only if the indifference threshold is strongly reduced and a weight of four is applied, would Reorg+Bin40 be surpassed by Reorg+BG4. Again the tails are not included but they show that BaU would stay in last position.

Fig. 4: sensitivity analysis of Electricity Production

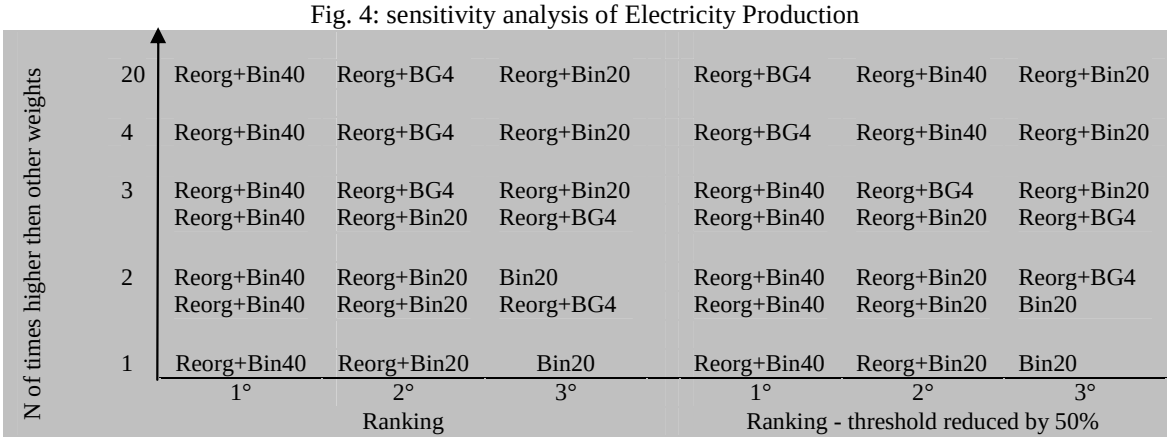
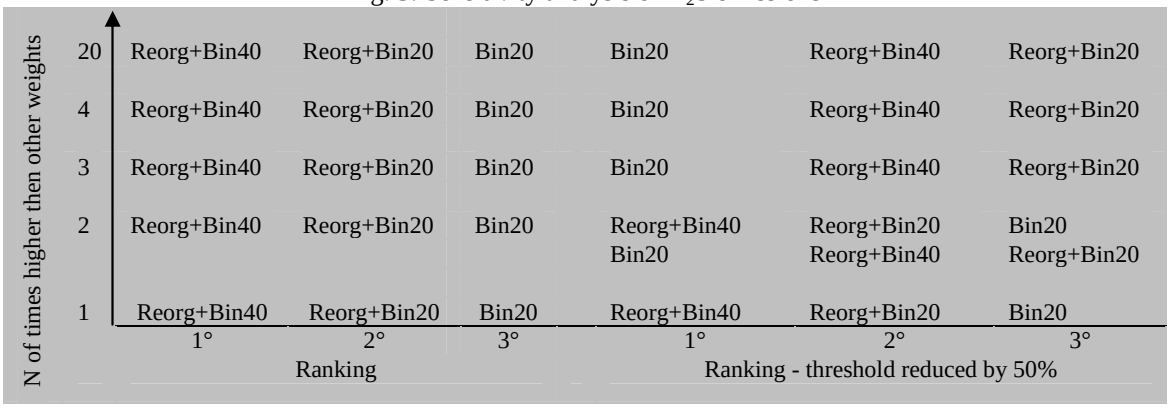


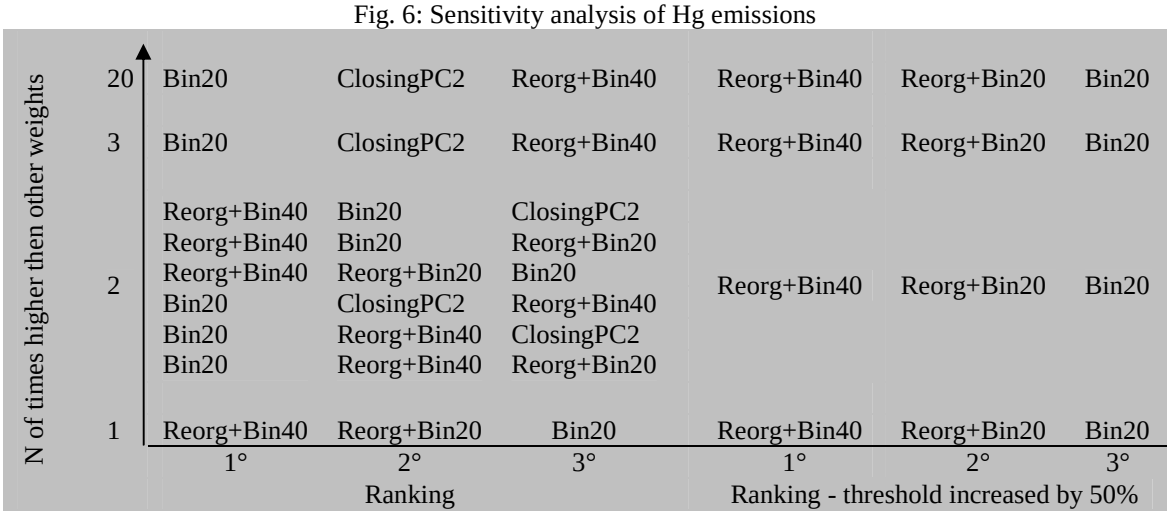
Figure 5 reports the same typology of analysis for the H_2S Emission criterion. Changes can be detected only by reducing the indifference threshold. In so doing, Bin20 would be the first option if the weight were doubled or tripled.

Fig. 5: Sensitivity analysis of H_2S emissions



The sensitivity analysis for the Hg emission criterion is depicted in Fig. 6. By increasing the weight of this criterion by three, Bin20 reach the first position and ClosingPC2 the second. So, when the emissions of Hg are actually considered as a major concern (e.g. because of further investigations announced by the regional government following the results of the epidemiological study) these alternatives could be justified. If the threshold value is increased by 50%, Reorg+Bin40 rank first, Reorg+Bin20 second, and Bin20 third.

Fig. 6: Sensitivity analysis of Hg emissions



The sensitivity analysis for the impact on aquifer is reported in Fig. 7. The use of binary cycles improves the position of the scenario. However, if the threshold value is reduced, ClosingPC2 and Bin20 rank better than the alternatives which include the reorganization plan.

Fig. 7: sensitivity analysis of Impact on aquifer

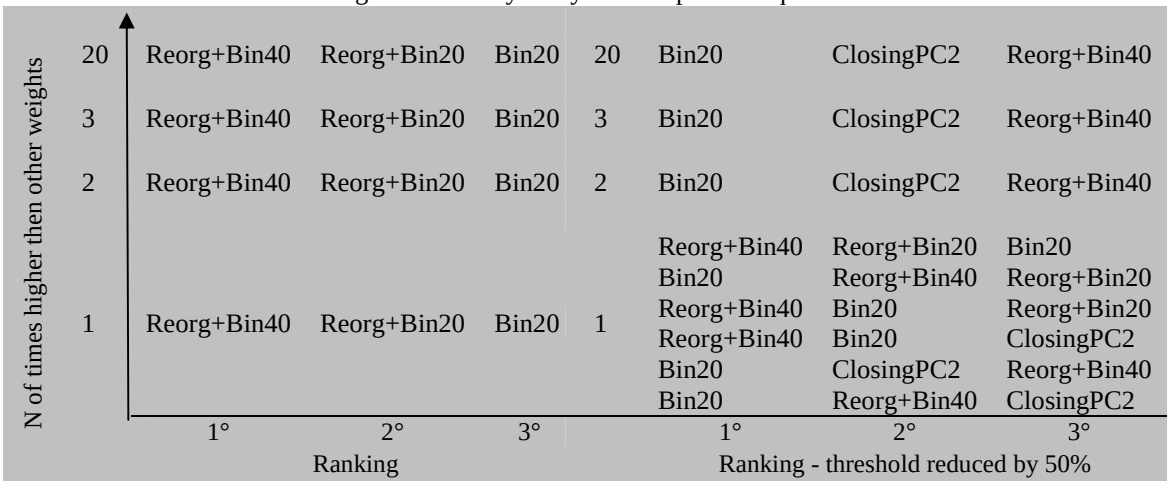
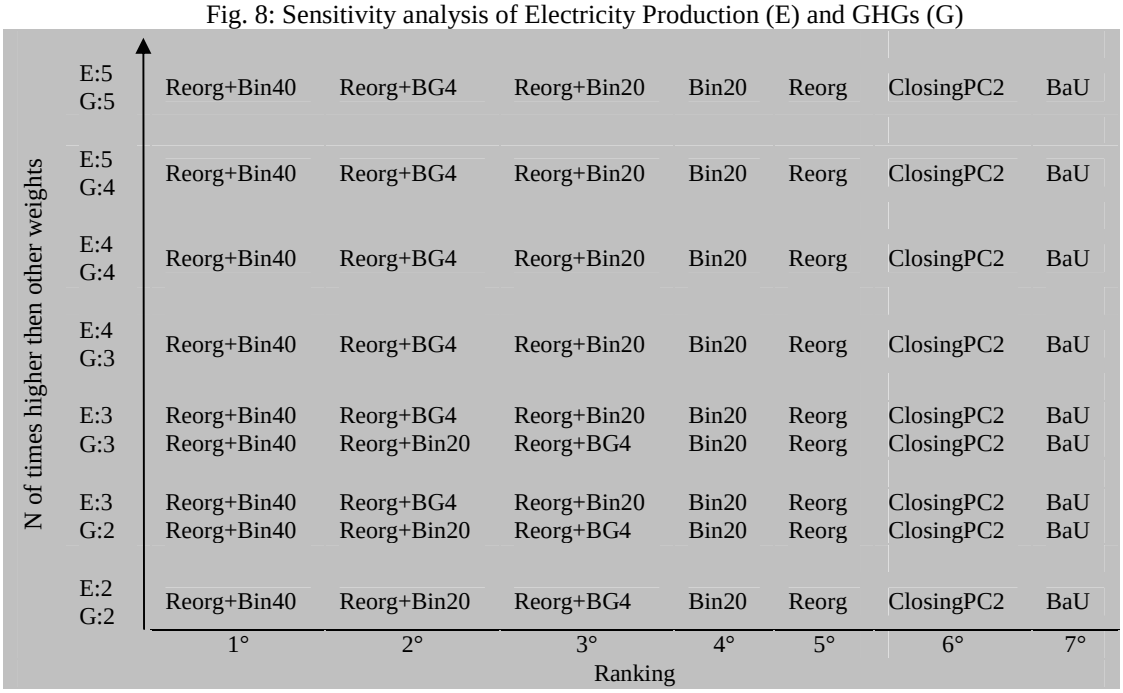


Figure 8 reports the sensitivity analysis obtained by changing the weights of the two criteria at the same time. The criteria are Electricity production and GHGs avoided. This type of analysis would reflect the importance of regional energy policies.

Fig. 8: Sensitivity analysis of Electricity Production (E) and GHGs (G)



Results were also calculated for the considered values of green certificates but the changes observed are minimal and are related only to the tails of the rankings.

6. Conclusions

The context of this work is characterized by strong uncertainty concerning crucial issues such as the impact of a given economic activity on human health and the conservation of an extremely precious resource: water. It is our contention that the problem presented here is a typical post-normal science problem, where “facts are uncertain, values in disputes, takes high and decisions urgent” (Funtowicz and Ravetz, 1993: p744). In post-normal science, the classical dichotomies of facts and values, and ignorance and knowledge are transcended. Incomplete control and a plurality of legitimate perspectives should be openly acknowledged. The social actors included in this study do have different legitimate perspectives and conflicting values. This paper has attempted to show how a social-multi-criteria evaluation can be applied in such a post-normal science case.

Decision making cannot accommodate all the legitimate claims from different social actors. Some people will benefit and others will be negatively be affected. If decision making is based on optimizing mono-disciplinary models, best alternatives could certainly (and easily) be identified. However, these optimizing models tend to

make the problems that have not been captured by the selected variables, reappear in a stronger form in other models. For example, profit-maximizing models, which cause ecological stress, and models that optimize ecological conservation variables, which imply profit compression and the absence of employment opportunities. In addition, by boosting the expected benefits of the selected mono-disciplinary variables in conditions of diverging perspectives, social and environmental conflicts can easily be aggravated. In fact, the social actors whose interests are not reflected by the selected variables will be negatively affected. This is why decision support tools should facilitate decision-making processes based on an interdisciplinary selection of variables, aimed at identifying compromise solutions rather than providing optimizing results.

The main objective of this work was not to indicate a definitive solution for the geothermal development scenarios in Mt. Amiata, but rather to explore possible alternatives in the light of different concerns and different points of view. The results do not intent do relieve policy makers of their responsibilities to take very difficult decisions but are aimed at shedding light on the consequences of specific options by assigning more or less importance to certain criteria and certain points of view. In this way, the paper contributes to the decision-making process by modeling preferences through weights and criteria. The ultimate hope is to have contributed to making the decision-making process more transparent.

With this caveat, some tentative conclusions for this specific case study are reported. Current scenarios become the worst of all considered alternatives when criteria have an equal weight. In addition, current scenarios never get beyond the penultimate position by changing relative weights. The two projects proposed by ENEL become the first option when the profitability criterion weighs at least four or five times more than all the others. Between these two extremes lie various alternatives, and their rank depends on the weights of the criteria. Therefore depending on the relative weights, this work provides some answers for the decision-making process. Binary cycles tend to move the given alternatives between the highest positions. Regarding social reactions, the alternatives which include the so-called reorganization plan would be vetoed by three social actors based in the east of the mountain. The scenarios reflecting the views of the residents committees (i.e. ClosingPC2) rank between best positions when air emissions or impact on aquifer acquire more importance. Specifically, it is in the first position when Hg emissions are at least twice as high as the others, or when the importance of H_2S emissions is at least two/three times along with an halving of the indifference threshold. The same scenario is in the second position when the weight of As emissions is al least two/three times higher then the others. Moreover, it would obtain the second position when the weight of the impact on aquifer criterion is doubled along with an halving of the indifference threshold. One social compromise alternative could be the installation of binary cycles on the west side. However, the position of the different social actors is not determined once and for all, and opposition may become stronger when the feasibility of a given project becomes a concrete option. In addition, the installation cost of a 20MW binary cycle plant should probably be subsidized in addition to the envisaged green certificate price.

It is worth recalling that a specific criterion for employment effects was not included. The reasons for this were explained in Section 4.2 and include the lack of data and the fact that employment was never indicated as being important by the interviewees. This is because the number of permanent employees in the geothermal industry in Mt. Amiata is small and is not expected to grow significantly in the expansion scenarios. However, inclusion of employment effects for the limited period of the construction phase of the scenarios, comprising new investments would probably have provided different results. Moreover with a larger scale analysis, the effects on ancillary industries could also be included.

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Appendix A1 – Summary of the interviews

Table A1: Interviews

Social actor	Participants	Place	Date
Piancastagnaio municipality	Mayor	Mountain authority office, Arcidosso	09/03/2011
Santa Fiora branch Communist Party	1	Santa Fiora	09/03/2011
Arpat	1	Arpat office, Siena	11/03/2011
Prospettiva Comune Piancastagnaio	3	Piancastagnaio	17/03/2011
WWF	1	Monte Labbro	17/03/2011
Comitato per la Tutela dell'Ambiente dell'Amiata - Abbadia San Salvatore	3	Abbadia San Salvatore	18/03/2011
Arcidosso municipality	Mayor	Town hall, Arcidosso	18/03/2011
Rete Comitati per la Difesa del Territorio	1	Abbadia San Salvatore	18/03/2011
Enel Green Power Ricerche	2	Enel Green Power office, Pisa	22/03/2011
Residents' association of Arcidosso (no more active)	1	Arcidosso	25/03/2011
Santa Fiora Municipality	Mayor Mayor's deputy	Mountain authority office, Arcidosso	26/03/2011
Abbadia San Salvatore Municipality	Mayor	Florence	05/04/2011