Journal of Cleaner Production 66 (2014) 301–308

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental impact of electricity from selected geothermal power plants in Italy

Mirko Bravi [b], Riccardo Basosi [a,*]

[a] Dept. of Chemistry, Univ. of Siena, Via A. Moro 2, 53100 Siena, Italy
[b] Department of Energy & Syst. Eng., Univ. of Pisa, Largo Lucio Lazzarino, 56122 Pisa, Italy

ARTICLE INFO

Article history:
Received 12 April 2013
Received in revised form
8 November 2013
Accepted 8 November 2013
Available online 18 November 2013

Keywords:
Geothermal
Electricity
Power plants
Environmental impact
Life cycle assessment
Renewable energy

ABSTRACT

Geothermal plants supply a significant contribution to the electricity balance from renewable sources in Tuscany. However, this electricity conversion is not exempt from environmental drawbacks.

In our study, the electricity production phases of four geothermal electricity plants are analyzed by means of a careful airborne emissions assessment carried out over the entire LCA of the plants. The impact categories considered are global warming (GWP), acidification (ACP) and human toxicology (HTP). The functional unit used is 1 MWh of electric energy produced from geothermal power plants in Mount Amiata area.

For the environmental impact categories considered, the impact potentials are evaluated for each of the four geothermal power plants as follows: 380–1045 kg CO_2 eq/MWh for GWP, 0.1–44.8 kg SO_2 eq/MWh for ACP and 1.1–31.6 kg, 1.4-DB eq/MWh for HTP. The main contributions to the impact are associated with the high content of NH_3, H_2S, CH_4 and CO_2 gases present in the effluents of each plant. The impact change in relation to the geothermal site has a strong correlation to the basin of fluid withdrawal and is related to the technologies used for pollutants depletion. In some cases the impact is higher than that found for production of electricity from fossil fuels (for example, a coal plant of comparable power).

1. Introduction

The production of geothermal energy in Italy began (by the beginning of the twentieth century) with the exploitation of the geothermal field of Larderello, Italy (Barbier, 2002). Currently in Italy 882.5 MWe (772 MWe net power) geothermal plants are installed (Terna, 2010) with a production of 1.8% of the electricity generated at national level. In Tuscany, geothermal power accounts for about 25% of total annual electricity production (Cappetti et al., 2010). In 2011, the production of geothermal power plants located in the Province of Siena (with a total capacity of 180 MW) was 1325 GWh which represented more than 100% of the 1316 GWh, the total annual consumption of the Siena province.

The objectives of geothermal development in Italy, and, in particular, in the Tuscany region, are related to the development of thermal use and to the increase of the production of electricity from renewable sources, in order to lessen dependence on fossil fuels and to reduce CO_2 emissions. These objectives are in agreement with international Protocols such as the Kyoto Protocol and the EU Directive 2009/28/EC on renewable energy sources. Electricity is one of the vectors that is more advantageous and versatile due to its easy transportation and the fact that it has an impact only where is produced and not where it is used.

Therefore, as a precondition for the intensification of exploitation, it is important to understand the environmental characteristics of geothermal power generation and to find solutions to minimize the impact. The geothermal resource is site specific (like all mineral resources), since its location is determined by geo mineralogical phenomena that have allowed the formation, accumulation and storage. Mount Amiata is a dormant volcano, located in the provinces of Siena and Grosseto in the southern part of the Tuscany region. The exploitation of geothermal resources there began in 1960. In the 1990's, a high enthalpy geothermal well was discovered at a depth of about 2.5–4 km with temperatures of

---

List of abbreviations: GWP, Global Warming Potential; ACP, Acidification Potential; HTP, Human Toxicity Potential; BG3, Bagnore 3 geothermal power plant; PC (3, 4 and 5), Piancastagnaio geothermal power plants.

* Corresponding author. Tel.: +39 (0)577234240; fax: +39 (0)577234239.
E-mail addresses: mirko.bravi@lmsenergia.com (M. Bravi), riccardo.basosi@unisi.it, basosi@unisi.it (R. Basosi).

0959-6526/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2013.11.015

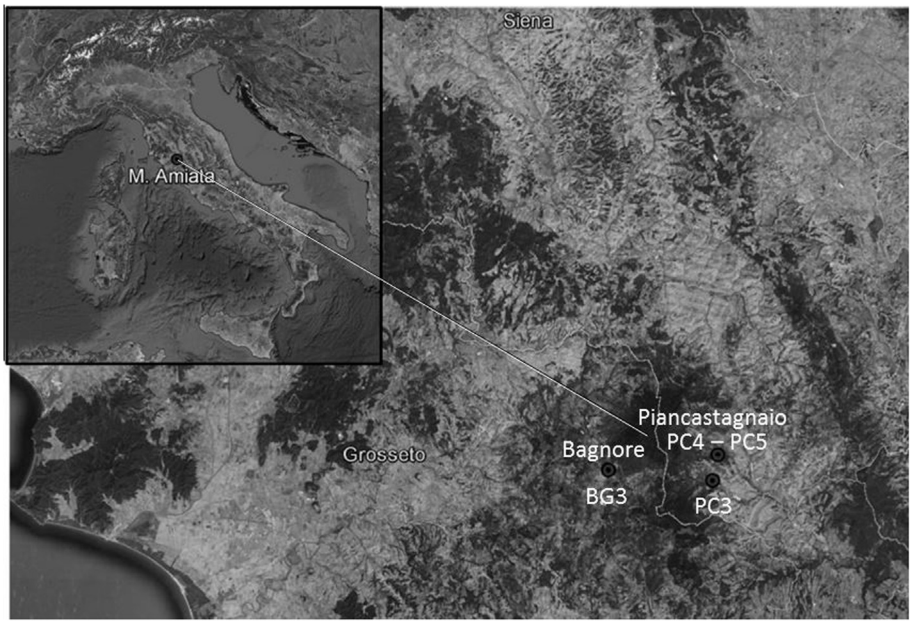

Fig. 1. Map of Monte Amiata area including all locality names and power plant locations mentioned in the study.

300–350 °C and pressures around 20 MPa which had high potential for electricity production (Bertani, 2012).

Many studies in literature deal with the environmental impact associated with the production of geothermal electricity. Hagedoorn (2006) provides a general overview of these. Other studies have focused on the sustainable production of geothermal resources and suggest the use of models for the management of geothermal fields (Axelsson and Stefansson (2003)). Bertani and Thain (2002) and Bloomfield et al. (2003) argued that the natural discharge of CO_2 from geothermal fields is probably higher than that of CO_2 emissions from energy use in the same field. Furthermore Bertani and Thain (2002) concluded that CO_2 emissions from geothermal plants are balanced by a reduction in natural release of CO_2 from geothermal fields. Following this line of thought, the European community does not include Greenhouse gas emissions produced from geothermal power plants in the burden shares allocated to countries. Consequently, in Italy and the rest of Europe, greenhouse gas inventories do not take into account CO_2 emissions from geothermal plants.

The life cycle inventories of electricity production in different networks have been carefully reviewed by Itten utilizing for geothermal (and tidal) electricity production the model and data set for wind power (Itten et al., 2012). More recently a comprehensive review on life cycle environmental effects of geothermal power generation has been published by Bayer et al. (2013) concluding that it is crucial the influence of site-specific characteristics.

Armannsson, referring to Iceland where natural phenomena are more visible than in Italy, doubts that CO_2 emissions from electricity plants are negligible (Ármannsson et al., 2005).

Frondini et al. (2009) argue that it is likely that natural emissions in Mount Amiata area due to volcanic degassing are much lower than those due to the exploitation of geothermal fluids at a considerable depth (as the wells feeding the plants considered in this study). In the past, most studies have focused mainly on liquid emissions (where the greatest progress has been made) and which are the most malodorous and for which the need for urgent removal was considered (Bacci, 1998). At the end of twentieth century the mercury emission rates ranged from 3 to 4 g/MWh of electric energy production in the Amiata area. These emissions were coupled with a release of 7–8 kg/MWh of hydrogen sulphide (Bacci et al., 2000).

In our study, we developed an impact potential analysis, based primarily on non-condensable gases emitted from geothermal power plants in the area.

Table 1
The description of the four geothermal power plants.

Description of the study site	Bagnore 3	Piancastagnaio 3	Piancastagnaio 4	Piancastagnaio 5
Geographic coordinates WGS84	42.842/11.558	42.833/11.700	42.857/11.705	42.856/11.702
Province	Grosseto	Siena	Siena	Siena
Acronym	BG3	PC3	PC4	PC5
Installed capacity, MWe	20	20	20	20
Starting date	17/12/1998	04/05/1990	28/11/1991	02/02/1996
Abatement technologies	AMIS (Abatement of mercury and hydrogen sulphide)	AMIS	None (AMIS was installed in late 2008)	AMIS
Type of unit	Single Flash	Steam with entrained water separated at wellhead		
Well Depth, km	From 2 to 4			
Temperature, °C	Between 300 and 350			
Pressure, MPa	Around 20			
Annual Energy Produced 2008, GWh/y	169.7	160.4	139.1	145.3

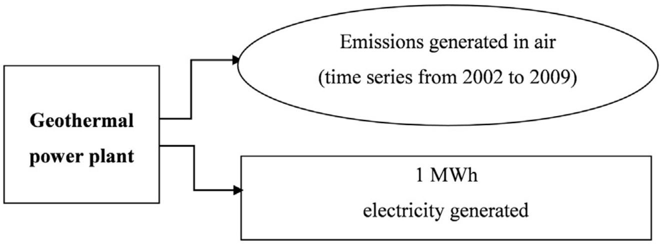

Fig. 2. Basic system boundary of geothermal power plant.

2. Materials and methods

2.1. *Goal and scope*

This research aims to evaluate the environmental impact of selected geothermal power plants from an environmental assessment perspective and furthermore, to provide environmental information on the production of electricity from existing geothermal power plants in Mount Amiata (Tuscany, Italy).

In particular, we analyzed the emissions of non-condensable gases of geothermal fluids in the period 2002–2009. Only the production phase of the four geothermal power plants was considered by analysing the output of the emission materials from the chimneys. A map of Monte Amiata area including all locality names and power plant locations involved in the study is reported in Fig. 1

The consumption of resources associated with the drilling, construction, and operation of the wells and the additional materials needed for the construction and operating of geothermal plants have not been included. This is because the impact of plant construction is diluted over the assumed 25 years of plant operation and only account for a small amount of total foreground and background emissions (2% of yearly CO_2 emissions, 1% of yearly fossil energy use, 1% of annual matter flows, according to Ulgiati and Brown (2002). However, in future work we plan to include the plant construction steps in order to compare different geothermal technologies available on the market.

2.2. *Description of the study site*

Mount Amiata is a dormant volcano with a height of 1738 m located in southern Tuscany. The area is very rich in minerals with mercury, which was extracted in ancient times. The geothermal gradient in this area is very high and varies from 100 to 250 °C/km. The geothermal field of Monte Amiata is water dominant with high temperatures. Currently there are four active geothermal plants:

- 1 unit in the Bagnore site that covers an area of 5 km^2 consisting of 7 production wells and 4 injection wells;
- 3 units in Piancastagnaio site that covers an area of 25 km^2 consisting of 19 production wells and 11 injection wells (Frondini et al., 2009).

Table 1 shows the main characteristics of the four geothermal power plants considered; Bagnore 3 (BG3) and Piancastagnaio 3, 4 and 5 (PC3, PC4 and PC5).

2.3. *System boundaries*

The geographical and time boundaries of this study include the production phase of the geothermal plants, without considering the drilling, construction and decommissioning phases. We

Table 2
Averages and variability air emissions of geothermal power plant from 2002 to 2009.

Unit	kg/MWh											
Acronym	BG3			PC3			PC4			PC5		
	Average	Confidence interval		Average	Confidence interval		Average	Confidence interval		Average	Confidence interval	
		Min	Max		Min	Max		Min	Max		Min	Max
Hydrogen sulfide	1.53	9.90×10^{-01}	2.26	3.49	2.63×10^{-01}	$1.07 \times 10^{+01}$	8.01	6.79	9.24	3.05	3.97×10^{-02}	$1.14 \times 10^{+01}$
Arsenic	1.20×10^{-06}	5.73×10^{-07}	2.00×10^{-06}	6.64×10^{-06}	1.47×10^{-06}	1.64×10^{-05}	4.47×10^{-05}	4.56×10^{-06}	8.48×10^{-05}	1.92×10^{-05}	3.08×10^{-06}	3.53×10^{-05}
Mercury	1.03×10^{-06}	7.81×10^{-08}	2.93×10^{-06}	1.18×10^{-06}	1.96×10^{-09}	3.59×10^{-06}	1.17×10^{-06}	4.09×10^{-07}	1.94×10^{-06}	2.17×10^{-04}	1.35×10^{-08}	5.30×10^{-04}
Carbon dioxide	$3.98 \times 10^{+02}$	$2.45 \times 10^{+02}$	$6.56 \times 10^{+02}$	$4.65 \times 10^{+02}$	$4.13 \times 10^{+02}$	$5.00 \times 10^{+02}$	$5.29 \times 10^{+02}$	$4.73 \times 10^{+02}$	$5.85 \times 10^{+02}$	$6.77 \times 10^{+02}$	$5.54 \times 10^{+02}$	$7.79 \times 10^{+02}$
Ammonia	$1.41 \times 10^{+01}$	4.48	$2.89 \times 10^{+01}$	2.74	6.45×10^{-01}	7.83	5.11	2.96	7.25	1.55	8.59×10^{-02}	5.83
Arsenic compounds	2.66×10^{-05}	1.74×10^{-05}	4.64×10^{-05}	2.37×10^{-05}	1.90×10^{-05}	2.72×10^{-05}	9.70×10^{-05}	9.70×10^{-05}	9.70×10^{-05}	3.62×10^{-05}	3.62×10^{-05}	3.62×10^{-05}
Antimony compounds	1.02×10^{-05}	1.10×10^{-08}	2.05×10^{-05}	8.02×10^{-06}	1.68×10^{-08}	1.24×10^{-05}	7.88×10^{-05}	7.88×10^{-05}	7.88×10^{-05}	1.78×10^{-05}	1.78×10^{-05}	1.78×10^{-05}
Selenium	1.75×10^{-05}	4.87×10^{-08}	2.98×10^{-05}	2.59×10^{-05}	3.53×10^{-08}	5.98×10^{-05}	4.97×10^{-06}	4.97×10^{-06}	4.97×10^{-06}	8.59×10^{-05}	8.59×10^{-05}	8.59×10^{-05}
Mercury compounds	1.62×10^{-04}	6.19×10^{-05}	2.49×10^{-04}	6.94×10^{-04}	1.41×10^{-04}	1.82×10^{-03}	2.23×10^{-03}	1.05×10^{-03}	3.42×10^{-03}	1.20×10^{-03}	6.63×10^{-04}	1.75×10^{-03}
Cadmium	4.35×10^{-08}	1.49×10^{-09}	1.08×10^{-07}	3.14×10^{-08}	1.59×10^{-10}	9.24×10^{-08}	9.30×10^{-09}	1.64×10^{-09}	1.70×10^{-08}	1.17×10^{-08}	1.04×10^{-08}	1.30×10^{-08}
Chromium	2.83×10^{-07}	3.65×10^{-08}	5.15×10^{-07}	3.99×10^{-06}	9.73×10^{-09}	1.20×10^{-05}	4.06×10^{-07}	3.27×10^{-07}	4.85×10^{-07}	4.86×10^{-07}	5.21×10^{-08}	9.20×10^{-07}
Manganese	3.36×10^{-07}	1.79×10^{-07}	5.15×10^{-07}	1.77×10^{-07}	1.96×10^{-08}	4.57×10^{-07}	3.04×10^{-07}	8.77×10^{-08}	5.21×10^{-07}	1.63×10^{-07}	2.60×10^{-08}	3.01×10^{-07}
Nickel	6.88×10^{-07}	5.08×10^{-07}	1.04×10^{-06}	1.68×10^{-06}	2.16×10^{-08}	4.95×10^{-06}	8.29×10^{-07}	6.06×10^{-07}	1.05×10^{-06}	3.61×10^{-07}	3.44×10^{-07}	3.79×10^{-07}
Lead	2.60×10^{-07}	5.64×10^{-08}	5.15×10^{-07}	1.54×10^{-07}	1.95×10^{-09}	4.57×10^{-07}	5.17×10^{-08}	1.58×10^{-08}	8.77×10^{-08}	2.37×10^{-08}	1.30×10^{-08}	3.44×10^{-08}
Copper	3.67×10^{-07}	6.67×10^{-08}	7.73×10^{-07}	1.81×10^{-07}	1.52×10^{-08}	4.57×10^{-07}	1.35×10^{-07}	8.77×10^{-08}	1.82×10^{-07}	3.94×10^{-07}	5.21×10^{-08}	7.36×10^{-07}
Vanadium	1.89×10^{-07}	2.08×10^{-08}	5.15×10^{-07}	1.56×10^{-07}	3.51×10^{-09}	4.57×10^{-07}	4.81×10^{-08}	8.48×10^{-09}	8.77×10^{-08}	3.72×10^{-08}	1.30×10^{-08}	6.13×10^{-08}
Boric acid	8.57×10^{-03}	2.69×10^{-03}	1.49×10^{-02}	1.86×10^{-02}	2.26×10^{-03}	5.07×10^{-02}	2.30×10^{-02}	1.75×10^{-02}	2.85×10^{-02}	2.79×10^{-02}	1.18×10^{-02}	3.60×10^{-02}
Methane	9.81	5.77	$1.70 \times 10^{+01}$	5.45	2.31	8.84	8.20	4.21	$1.22 \times 10^{+01}$	6.96	5.03	7.91
Carbon monoxide	3.75×10^{-02}	1.65×10^{-02}	8.25×10^{-02}	3.64×10^{-02}	6.85×10^{-03}	5.35×10^{-02}	2.43×10^{-02}	1.76×10^{-02}	3.10×10^{-02}	6.38×10^{-02}	5.20×10^{-02}	7.25×10^{-02}

Table 3
The impact categories of characterization and their contributors.

Impact category	Abbreviation	Unit	Contributors of each impact category	Area impacted
Global warming (100 years)	GWP	kg CO_2 eq	CO_2, CH_4, N_2O, SF_6, CF_4, C_2F_6	Global impact
Acidification	ACP	kg SO_2 eq	SO*x*, SO_2, NO*x* NO_2, NH_3, HCl, HF, H_2S	Regional impact
Human toxicity	HTP	kg 1.4 DB eq	SO_2, NO*x*, As, Pb, Mn, Hg, Ni, Se	Regional impact

accounted for foreground emissions into the atmosphere exclusively in order to evaluate the potential impact associated with geothermal power plants production of electricity. Due to the dilution of construction phase emissions, the partial underestimate of the calculated impact, with respect to the actual total environmental impact, does not affect the main conclusions of the study. The basic system boundary of geothermal power plant for this study is shown in Fig. 2.

The functional unit of this study is 1 MWh electric energy production from a geothermal power plant in the Mount Amiata area.

2.4. Inventory

The inventory data for this study are taken from air emissions of geothermal power plant inventories from ARPAT (Tuscany Regional Agency for Environmental Protection) during the period 2002–2009 (ARPAT, 2012).

In Table 2, we report the type of air emissions, the average value and the variability for each plant in the sample. Each value was normalized with respect to the functional unit using the values of power plants inventoried from ARPAT during the test. Sampling was performed with the following temporal frequency: BG3 years 2002, 2004, 2005, 2006, 2008 and 2009; PC3 years 2002, 2004, 2005, 2006, 2007, 2008 and 2009; PC4 years 2002, 2008 and 2009; PC5 years 2002, 2007, 2008 and 2009.

2.5. Impact assessment

The environmental impact assessment was conducted using the SimaPro software (Prè Consultants, 2011) and CML 2002 (Prè Consultants, 2008) baseline methodology. The results for the three environmental impact categories included in this study are listed in Table 3 along with the possible contributing environmental loads. The detailed information about each impact in this study is explained in the following subsections.

The results of this study are being compared presently to two other power generation systems of comparable power, coal and natural gas. The environmental impact potential from electricity production of these two kinds of fossil fuels are shown in Table 4. They are taken from the Ecoinvent database (Frischknecht et al., 2005; Emmenegger et al., 2007; Roder et al., 2007), where five stages were considered: before construction, construction, transportation, operation and maintenance, and demolition of power plants. Not considering all the previous stages does not significantly affect the validity of the comparison proposed in the present study. In fact, for the electricity produced by coal-fired and natural gas, GWP, ACP and HTP impact categories, are predominantly due to direct emissions during the operation of the power plant. In particular, the operation phase accounts for 95% of GWP in coal and 83% in gas plants and 87% and 40% of ACP and 79% and 64% of HPT respectively (Emmenegger et al., 2007; Roder et al., 2007).

Table 4
Environmental impact potentials of electric energy (1 MWh) at power plant.

Fuel	Coal	Natural gas
GWP (kg CO_2 eq)	$1.06 \times 10^{+03}$	$6.40 \times 10^{+02}$
ACP (kg SO_2 eq)	5.05	6.12×10^{-01}
HTP (kg 1.4 DB eq)	$8.71 \times 10^{+01}$	$6.94 \times 10^{+01}$

3. Results

Geothermal power plants in the Mount Amiata area emit in air a high variety of non-condensable products (CO_2, H_2S, NH_3, CH_4). Carbon dioxide is the main emission from the geothermal field, the actual range being from 245 to 779 kg/MWh with the weighted average being 497 kg/MWh. Ammonia emissions range between 0.086 and 28.94 kg/MWh with a weighted average of 6.54 kg/MWh. Emissions of NH_3 per MWh in the geothermal field of Bagnore are about 4 times higher than those recorded in the central exploitation of the geothermal field of Piancastagnaio. Peak values of the various samples are 15 times higher than the maximum concentrations detected by Barbier (2002) which range between 57 and 1938 mg/kWh. Natural gas has an average of 7.54 kg/MWh, with values ranging at the time of the series sampling from 2.3 to 16.9 kg/MWh. Also, in this case the values of Bagnore are higher by more than 50% compared to the average values of Piancastagnaio.

Hydrogen sulfide has a mean range of 3.24 kg/MWh, with values varying between 0.4 and 11.4 kg/MWh. In this case, the average values of Piancastagnaio are 4 times higher than those of the geothermal field of Bagnore. These values are related to the characteristics of the geothermal fluid and to the fact that (PC4) only since the end of 2008, has PC4 been equipped with AMIS (Abatement of mercury and hydrogen sulfide) (Baldacci et al., 2005). Peak values of the various samples are about 2 times higher than the maximum concentrations detected by Barbier (2002) that range from 0.5 to 6.8 g/kWh.

Geothermal gases emitted from the power plants also contain traces of mercury (Hg), arsenic (As), antimony (Sb) selenium (Se) and chromium (Cr).

Mercury emissions range between 0.063 and 3.42 g/MWh with a weighted average of 0.72 g/MWh. Peak values of the samples are about 3.8 times higher than the maximum concentrations detected by Barbier that ranged from 45 to 900 g/kWh.

The results of the three environmental impact categories considered in the study in the period 2002–2009 are summarized in Table 5, while the detailed information about each impact is explained in the following subsections.

3.1. Global Warming Potential (GWP)

Fig. 3 shows the dynamics of GWP through the years. The greenhouse gases emissions from geothermal power plants cannot be considered negligible.

The GWP average value is 693 kg CO_2 eq/MWh, with values ranging between 380 and 1045 kg/MWh. Using ecoinvent database v.2, we calculated the GWP impact category for the electric energy produced by coal-fired and natural gas respectively 1068 and 640 kg CO_2 eq/MWh. These values take into account the whole life cycle of plants including production, construction and disposal and provide reference data used to assess the potential impact of geothermal electricity production.

Table 5
Environmental impact potentials of all four geothermal power plants in M. Amiata for different years between 2002 and 2009.

Acronym	BG3	PC3	PC4	PC5	Average
Year	2002				
GWP (kg CO_2 eq)	$4.52 \times 10^{+02}$	$6.18 \times 10^{+02}$	$6.82 \times 10^{+02}$	$8.14 \times 10^{+02}$	$6.41 \times 10^{+02}$
ACP (kg SO_2 eq)	7.18	$1.25 \times 10^{+01}$	$1.16 \times 10^{+01}$	9.33	$1.02 \times 10^{+01}$
HTP (kg 1.4 DB eq)	1.16	9.03	4.39	4.18	4.69
Year	2004				
GWP (kg CO_2 eq)	$3.81 \times 10^{+02}$	$5.72 \times 10^{+02}$	n.a.	n.a.	$4.76 \times 10^{+02}$
ACP (kg SO_2 eq)	$2.02 \times 10^{+01}$	5.76	n.a.	n.a.	$1.30 \times 10^{+01}$
HTP (kg 1.4 DB eq)	1.73	7.95	n.a.	n.a.	4.84
Year	2005				
GWP (kg CO_2 eq)	$8.64 \times 10^{+02}$	$5.50 \times 10^{+02}$	n.a.	n.a.	$7.07 \times 10^{+02}$
ACP (kg SO_2 eq)	$4.48 \times 10^{+01}$	2.42	n.a.	n.a.	$2.36 \times 10^{+01}$
HTP (kg 1.4 DB eq)	3.43	1.10	n.a.	n.a.	2.26
Year	2006				
GWP (kg CO_2 eq)	$6.08 \times 10^{+02}$	$6.83 \times 10^{+02}$	n.a.	n.a.	$6.45 \times 10^{+02}$
ACP (kg SO_2 eq)	$3.44 \times 10^{+01}$	4.74	n.a.	n.a.	$1.96 \times 10^{+01}$
HTP (kg 1.4 DB eq)	3.32	5.38	n.a.	n.a.	4.35
Year	2007				
GWP (kg CO_2 eq)	n.a.	$5.28 \times 10^{+02}$	n.a.	n.a.	$5.28 \times 10^{+02}$
ACP (kg SO_2 eq)	n.a.	2.54	n.a.	n.a.	2.54
HTP (kg 1.4 DB eq)	n.a.	3.82	n.a.	n.a.	3.82
Year	2008				
GWP (kg CO_2 eq)	$1.04 \times 10^{+03}$	$5.88 \times 10^{+02}$	$7.53 \times 10^{+02}$	$7.22 \times 10^{+02}$	$7.77 \times 10^{+02}$
ACP (kg SO_2 eq)	$1.32 \times 10^{+01}$	2.00	4.74	2.42×10^{-01}	5.05
HTP (kg 1.4 DB eq)	2.98	2.98	$3.16 \times 10^{+01}$	$1.44 \times 10^{+01}$	$1.30 \times 10^{+01}$
Year	2009				
GWP (kg CO_2 eq)	$7.96 \times 10^{+02}$	$6.82 \times 10^{+02}$	n.a.	$8.50 \times 10^{+02}$	$7.76 \times 10^{+02}$
ACP (kg SO_2 eq)	$1.40 \times 10^{+01}$	1.03	n.a.	1.86×10^{-01}	5.09
HTP (kg 1.4 DB eq)	3.28	1.48	n.a.	$1.45 \times 10^{+01}$	6.42

Our results for the plants considered in this study are in good agreement with findings of Brown and Ulgiati (2002) who claim that the emission of CO_2 from geothermal energy is of the same order of magnitude as that of fossil power plants. This general statement should be treated with caution since it is likely that the nature of the geological stratigraphy, the geothermal system and the characteristics of the wells influence the size of the GWP impact potential. In fact, it can be reasonably argued that fractures generated from geothermal wells, reaching a 3500 m depth with a diameter of 30″ on the surface and 8.5″ in the head, increase geothermal fluids and CO_2 flow towards the surface in a completely unnatural mode. In the Mount Amiata area, the process of geothermal exploitation increases the process of natural CO_2 generation. In a different area, the result might be different.

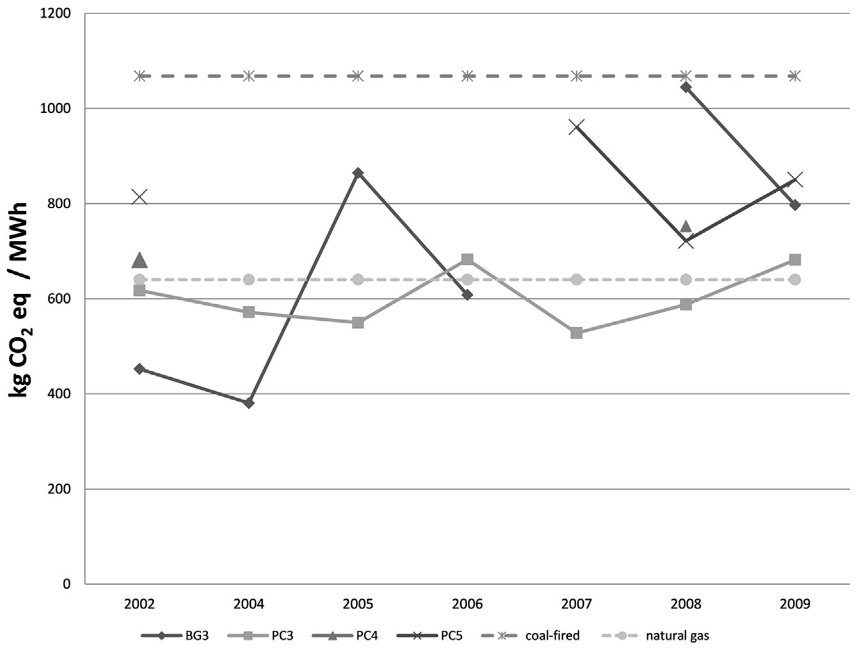

Fig. 3. Dynamics of greenhouse gas emissions from geothermal power through the years.

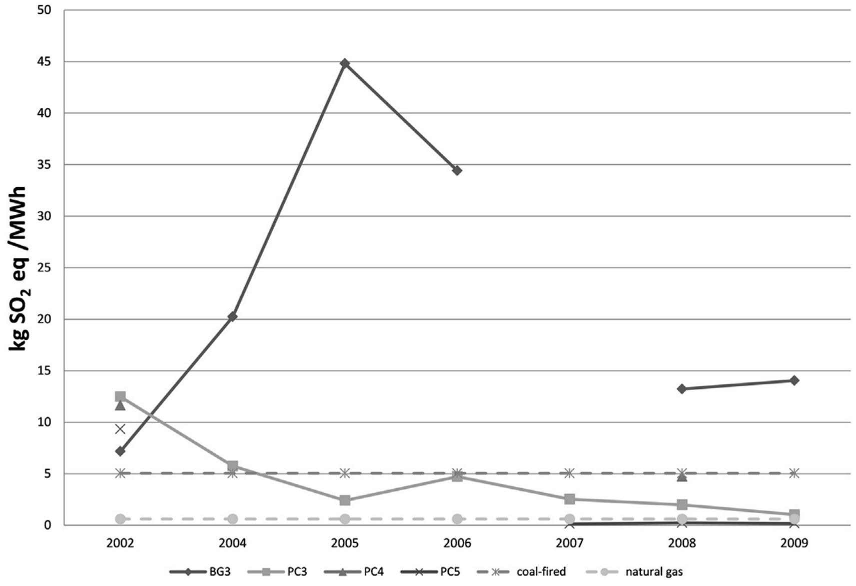

Fig. 4. Dynamics of Acidification Potential from geothermal power plants in the period studied.

3.2. Acidification Potential (ACP)

Fig. 4 shows the dynamics of ACP in the period studied. As in the case of GWP emissions, ACP emissions from geothermal power plants are not negligible.

The ACP average value is 12.5 kg SO_2 eq/MWh, with values that range between 0.1 and 44.8 kg/MWh. Electric energy produced by coal and natural gas has values equal to 5.1 and 0.6 kg SO_2 eq/MWh respectively. These values take into account the entire life cycle of the plants and provide references to assess the potential impact of geothermal electricity production. The comparison shows that from the point of view of the ACP, the impact from energy produced from the geothermal power plants of Mount Amiata is on average 2.2 times larger than the impact from a coal plant. The ACP average value of BG3 (the geothermal field of Bagnore 21.9 kg SO_2 eq/MWh) is 4.3 times higher than a coal power plant and about 35.6 times higher than a natural gas power plant. High values of ACP from the geothermal field of Bagnore with respect to Piancastagnaio as well, are connected to the large quantity of ammonia (NH_3) present in the output gases of BG3.

3.3. Human Toxicity Potential (HTP)

Fig. 5 shows the dynamics of HTP for the period studied. HTP average calculated is 5.9 kg 1.4 DB eq/MWh, with values ranging between 1.1 and 31.6 kg/1.4 DB eq/MWh.

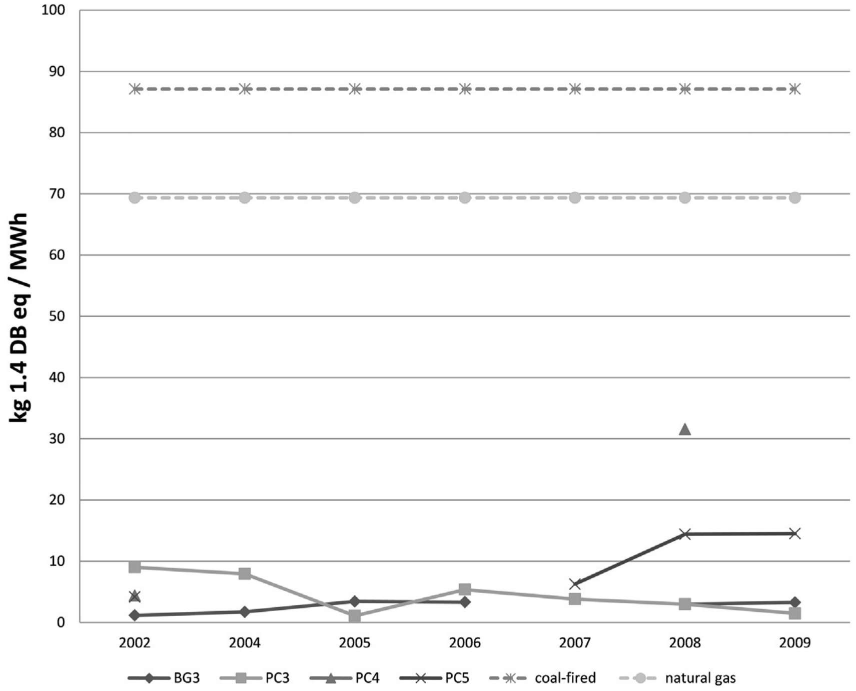

Fig. 5. Dynamics of Human Toxicity Potential from geothermal power plants for the period studied.

For electric energy produced from coal or natural gas, the calculated HTP values are 87.1 and 69.4 kg 1.4 DB eq/MWh respectively. These values take into account the entire life cycle of the plants while recalling that for the geothermal power plant we consider only operation phase. The comparison shows that, from the point of view of the HTP, the energy produced from geothermal power plants of Mount Amiata have on average 15.2 times less impact than a coal plant. In 2008, the high value of PC4, 31.6 kg 1.4 DB eq/MWh, (when compared to the average values of the other geothermal plants) is mainly due to the presence of high concentrations of mercury, sulfuric acid, boric acid, arsenic and antimony.

4. Discussion

In general, geothermal drilling creates fractures over 3000 m deep that increase the permeability of both geothermal fluids and non-condensable gases. The amount of gases and metals contained in geothermal fluids depends on several factors: depth and location of the geothermal reservoir; characteristics of the electricity generation (flash, binary, or combined cycle) and the abatement systems. To make Mount Amiata geothermal plants “carbon free” and environmentally sustainable, 100% of the geothermal fluids with incondensable gas should be re-injected into the same geothermal reservoir. This is possible in principle by using binary cycle technology (Frick et al., 2010; Lacirignola and Blanc, 2013). This new installation technology is probably more expensive and may have a lower electrical efficiency than the technologies currently used in the Mount Amiata geothermal fields, but at the same time, (since it is a closed cycle) it decreases the pressure on the environment. It also offers more guarantees in terms of geothermal resource sustainability. In the opinion of authors of a recent study based on multi-criterion evaluation of potential technological alternatives, the application of binary cycle technology is the most suitable scenario for the exploitation of geothermal resources in the Mount Amiata fields (Borzoni, 2012; Borzoni et al., 2012). In our opinion, a geothermal resource should always be exploited where it exists, both for heating and electricity production in an integrated way. The major limit to this exploitation of a natural important resource can arise from inadequate technologies that do not minimize the environmental impact, as they are conceived essentially to maximize the production of electricity.

Even though flash technology is the current standard for high-pressure, water dominated geothermal reservoirs such as the Amiata deep reservoir (Barelli et al., 2010), a sound choice of the working fluid (such as a mixture of hydrocarbons or refrigerants or Kalina water-ammonia) can guarantee optimized coupling to a high-temperature geofluid heat recovery network, avoiding circuit depressurization, or limiting this last to marginal recompression of incondensable gases. This is certainly a technical challenge since the circuit pressure is very high, however, it is within current technology. In fact, supercritical steam power plants have been operational for more than 40 years and ultra-high pressure gas compressors for aggressive chemical species have been developed in the oil and gas industry. The added cost with respect to a conventional double-flash solution can be compensated to some extent by the improved coupling between the geofluid and working fluid temperature profiles. This approach allows for a reduction in heat transfer irreversibility. A binary plant might be by no means the ultimate solution. It is also possible that a hybrid flash-binary plant, with recovery, recompression and reinjection of condensables and incondensables, would be a more viable option for the Amiata field. However, the purpose of this paper is not to propose the “correct” technical solution, but rather to assess what would be the potential environmental performance of a complete closed-loop (full-reinjection) geothermal power station, compared to the current technology. In principle, the atmospheric condensation could be integrated in a flash technology as well, using an air condenser and reinjecting the incondensable gases, but technical problems connected with the process irreversibility would not be overcome easily.

In general, although much has been done already to eliminate the local impact with AMIS procedures, further technological development is necessary to mitigate the global environmental impact as the GWP.

5. Conclusions

In this study, an environmental assessment method was used to analyze the environmental impact in the atmosphere of electricity production from geothermal plants. In some cases, the impact of geothermal electricity production is even higher than that for producing electricity from fossil fuels.

Analysis shows that electricity from the geothermal plants in Mount Amiata area cannot be considered “carbon free” as claimed so far on the basis of literature mentioned in the introduction. Although Human Toxicity Potential did not provide worrisome values, greenhouse gas emissions are in some cases generally higher than those from natural gas plants and in some sampling not very far from the values of coal plants. Furthermore, the Acidification Potential of electricity produced from geothermal plants considered here is 2.2 times higher than that for coal plants. In the case of the Bagnore geothermal field this difference increases by a factor of 4.4 and is about 28 times higher than the ACP of natural gas plant.

The obvious inconsistency between geothermal electricity production and emissions by natural processes over long geological time cycles (which put the gases contained in geothermal fluids in contact with the atmosphere) cannot be ignored. Thus, there is a need for the development of appropriate technologies to reconcile the geothermal electricity plants with the renewable nature of the energy resource.

While it is true that the binary cycle technology is not, at the moment, the best solution from the point of view of efficiency and cost, the idea of considering the minimization of impacts (through the complete reinjection of incondensable fluids into the reservoir) is necessarily a promising avenue based on environmental considerations for geothermal power plants in the future.

In any case the financial profit should not be the main criterion in the decision-making process for development of geothermal plants in the Amiata area.

Acknowledgments

Authors wish to acknowledge the ARPAT (Tuscany Region) in particular, Dr. Marco Pellegrini for providing data and Prof. Eros Bacci and Prof. Giampaolo Manfrida for useful discussions. Careful reading and revising of the manuscript by Professor Emeritus Les Brooks, Sonoma State University, is gratefully acknowledged.

References

ARPAT, 2012. Tuscany Regional Agency for Environmental Protection (‘in Italian’). Geothermal Reports (‘in Italian’) 2002–2003; 2004; 2005; 2006; 2007–2008; 2009 http://www.arpat.toscana.it/temi-ambientali/aria/aree-geotermiche/ar_areegeotermiche.html (accessed 22.04.13.).

Ármannsson, H., Fridriksson, T., Kristjánsson, B.R., 2005. CO_2 emissions from geothermal power plants and natural geothermal activity in Iceland. Geothermics 34, 286–296. http://dx.doi.org/10.1016/j.geothermics.2004.11.005.

Axelsson, G., Stefansson, V., 2003. Sustainable management of geothermal resources. In: International Geothermal Conference, Reykjavik, Iceland, pp. 40–48. http://www.jardhitafelag.is/media/pdf/s12paper075.pdf (accessed 22.04.13.).

Bacci, E., 1998. Geothermal Energy, Jobs, Environmental Implications, Impact Minimization ('in Italian'). Book published by ARPAT Tuscany Regional Agency for Environmental Protection.

Bacci, E., Gaggi, C., Lanzillotti, E., Ferrozzi, S., Valli, L., 2000. Geothermal power plants at Mt. Amiata (Tuscany – Italy): mercury and hydrogen sulphide deposition revealed by vegetation. Chemosphere 40, 907–911. http://dx.doi.org/10.1016/S0045-6535(99)00458-0.

Baldacci, A., Mannari, S., Sansone, F., 2005. Greening of geothermal power: an innovative technology for abatement of hydrogen sulphide and mercury emission. In: Proceedings of the 2005 World Geothermal Congress, Antalya, Turkey. http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0251.pdf (accessed 22.04.13.).

Barbier, E., 2002. Geothermal energy technology and current status: an overview. Renew. Sust Energ Rev. 6, 3–65. http://dx.doi.org/10.1016/S1364-0321(02)00002-3.

Barelli, A., Ceccarelli, A., Dini, I., Fiordelisi, A., Giorgi, N., Lovari, F., Romagnoli, P., 2010. A review of the Mt. Amiata geothermal system (Italy). In: Proceedings of the 2010 World Geothermal Congress; Bali, Indonesia, pp. 25–29.

Bayer, P., Rybach, L., Blum, P., Brauchler, R., 2013. Review on life cycle environmental effects of geothermal power generation. Renew. Sust Energ Rev. 26, 446–463. http://dx.doi.org/10.1016/j.rser.2013.05.039.

Bertani, R., 2012. Geothermal power generation in the world 2005–2010 update report. Geothermics 41, 1–29. http://dx.doi.org/10.1016/j.geothermics.2011.10.001.

Bertani, R., Thain, I., 2002. Geothermal Power Generating Plant CO_2 Emission Survey. International Geothermal Association. IGA News, n. 49 http://www.geothermal-energy.org/publications_and_services/iga_newsletter.html (accessed 22.04.13).

Bloomfield, K., Moore, J.N., Neilson Jr., R.M., 2003. Geothermal energy reduces greenhouse gases. Geothermal Resour. Counc. Bull., 77–79. http://www.geothermal.org/articles/greenhousegases.pdf (accessed 22.04.2013).

Borzoni, M., 2012. Integrated Assessment of Renewable Energies for Decision Making: a Two-case Analysis. PhD thesis in the subject of Management, competitiveness and development http://www.phdmanagement.sssup.it/documenti/awarded/borzoni_thesis.pdf (accessed 22.04.13.).

Borzoni, M., Rizzi, F., Frey, M., 2012. Social-multi criteria evaluation of alternative geothermal power scenarios: the case of Mt. Amiata in Italy. In: Bi-annual Conference for Ecological Economics, Rio De Janeiro, Brazil. http://www.isee2012.org/anais/pdf/680.pdf (accessed 22.04.2013).

Brown, M.T., Ulgiati, S., 2002. Emergy evaluations and environmental loading of electricity production systems. J. Clean. Prod. 10, 321–334. http://dx.doi.org/10.1016/S0959-6526(01)00043-9.

Cappetti, G., Romagnoli, P., Sabatelli, F., 2010. Geothermal power generation in Italy 2005–2009 update report. In: Proceedings of the 2010 World Geothermal Congress, Bali, Indonesia. http://s3.amazonaws.com/zanran_storage/b-dig.iie.org.mx/ContentPages/790827127.pdf (accessed 02.09.12.).

Emmenegger, M.F., Heck, T., Jungbluth, N., 2007. Natural Gas; Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries. Ecoinvent Report n.5, pp. 25–45.

Frick, S., Kaltschmitt, M., Schroder, G., 2010. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Energy 35 (5), 2281–2294. http://dx.doi.org/10.1016/j.energy.2010.02.016.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent database: overview and methodological framework. Int. J. LCA 10 (1), 3–9. http://dx.doi.org/10.1065/lca2004.10.181.1.

Frondini, F., Caliro, S., Cardellini, C., Chiodini, G., Morgantini, N., 2009. Carbon dioxide degassing and thermal energy release in the Monte Amiata volcanic-geothermal area (Italy). Appl. Geochem. 24, 860–875. http://dx.doi.org/10.1016/j.apgeochem.2009.01.010.

Hagedoorn, S., 2006. Methodology for a Sustainability Analysis of Geothermal Power Plants. Final report thesis. Universiteit Utrecht Copernicus Institute.

Itten, R., Frischknecht, R., Stucki, M., 2012. Life Cycle Inventories of Electricity Mixes and Grid. ESU-services Ltd. http://www.esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf (accessed 22.04.13.).

Lacirignola, M., Blanc, I., 2013. Environmental analysis of practical design options for enhanced geothermal. Renew. Energy 50, 901–914. http://dx.doi.org/10.1016/j.renene.2012.08.005.

Prè Consultants, 2008. SimaPro Database Manual. Methods Library. Methodology report v. 2.2, pp. 9–11. The Netherlands www.pre.nl (accessed 22.04.13.).

Prè Consultants, 2011. SimaPro 7.3. Amersfoort, The Netherlands www.pre.nl (accessed 22.04.13).

Roder, A., Bauer, C., Dobes, R., 2007. Coal; Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and Other UCTE Countries. Ecoinvent Report n.5, pp. 46–69.

Terna SpA, 2010. Statistical Data on Electricity in Italy ('in Italian') http://www.terna.it/LinkClick.aspx?fileticket=3bH2jk4Fz14%3d&tabid=464&mid=2497 (accessed 22.04.13.).

Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for the dilution and abatement of process emissions. The case of electricity production. J. Clean. Prod. 10, 335–348. http://dx.doi.org/10.1016/S0959-6526(01)00044-0.