

Title: Environmental and social aspects of geothermal energy in Italy

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Highlights

An overview of measures to tackle environmental challenges posed by geothermal energy in Italy

Environmental protection measures in an international context

Lessons from studies on social acceptability of geothermal energy

The role of accurate, comprehensive and public information

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Keywords

Air emissions, water interference, noise, induced seismicity, Larderello, Mt. Amiata

Abstract

Geothermal plants have been producing power in Italy for more than a century. Since local opposition to geothermal development is often fuelled by incomplete and inaccurate environmental information, this paper provides a comprehensive description of the effect of geothermal development on the air, water and soil and investigates potential disturbance from noise, subsidence, and seismicity, as well as the visual impact on the local area. After discussing the risks associated with the geothermal development and the reference data, the paper describes the wide-reaching environmental monitoring and mitigation measures in Italy that have maintained impact values below the thresholds defined by European and Italian regulation. The social benefits for areas where geothermal energy is developed are also described, with the aid of case studies highlighting that citizens do not feel that they are sufficiently informed to have a voice in the innovation process. A regular and comprehensive review of the geothermal environmental and safety regime, as the one carried out in this paper, and a mutual exchange of knowledge between the different stakeholders should be strongly encouraged.

1. Introduction

Geothermal resources are abundant in Italy, ranging from resources for shallow applications (including heat pump technology), through to medium ($>90^{\circ}\text{C}$) to high ($>150^{\circ}\text{C}$) temperature systems at depths accessible only by wells (usually within 3-4 km). High temperature systems tend to be in tectonically active regions either in volcanic and intrusive or fault-controlled systems (Santilano et al., 2015 and ref. therein).

Geothermal resources are today mainly used for generating electricity and air conditioning by means of district heating (DH) and geothermal heat pump systems. The DH systems are mainly located in Tuscany in central Italy, and direct uses are common. The heat delivered by direct geothermal uses is 10,500 TJ generating 1,300 MWth, with about half of the installed capacity being for space heating (DHs and individual systems) (Conti et al., 2016).

Geothermal energy is the third thermal renewable energy source in Italy, after bioenergy and air-source heat pump systems, and supplies about 2% of the total renewable heat consumption. Thermal balneology was once very popular and until 2010 was the first sector of utilization but the number of customers has since fallen by about 5% (Conti et al., 2016). In total, the estimated capacity of geothermal direct uses in 2015 was 1,300 MWth, GSHP accounting for 42% (about 580 MWth), followed by thermal balneology (32%), DH (10%), fish farming (9%), agricultural (6%), and industrial uses (1%) (Conti et al., 2016).

Italy was the first country in the world to produce electricity from geothermal fluids and is Europe's top generator of electrical power from geothermal resources (sixth in the world) (Bertani, 2016).

All of the 34 power plants in operation (by Enel Green Power) in Italy are located in Tuscany, a region in central Italy, in the two "historical" areas of Larderello-Travale and Mt. Amiata (Figure 1). The net electricity generation was 5,871 GWh in 2016 (TERNA a, 2016). The installed capacity in Larderello and Mt. Amiata is 795 MWe and 121 MWe, respectively. In Italy geothermal power production has increased continuously due to the resources being managed effectively. After an initial exploitation of the shallow carbonate reservoir, limited to 1 km depth, the fluid production was increased thanks both to the positive results of deep drilling that revealed a reservoir hosted in the deep crystalline (metamorphic and granitic) rocks, and to the effects of the reinjection of separated water and condensed steam into the reservoirs. Geothermal contribution to electrical energy capacity in Italy is 1%, and 2% to the overall demand for energy (TERNA b, 2016).

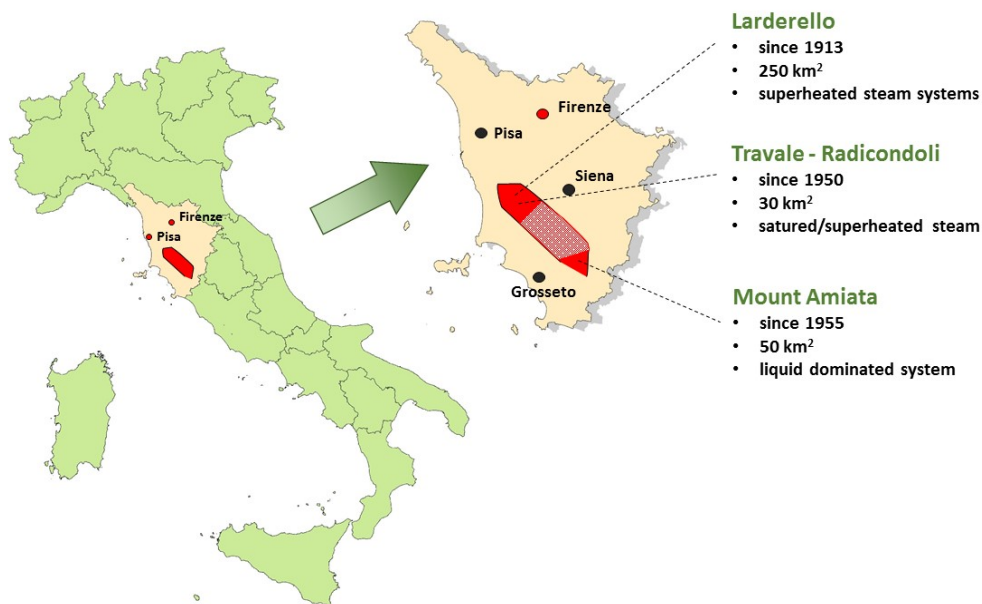


Figure 1 – Location of the geothermal areas producing electrical power in Italy.

Various legislation has regulated research into and the usage of geothermal energy in Italy.

In 2010, an LD liberalized research and exploitation of geothermal resource, and applied incentives for renewable sources. This led to several new players trying to enter the market, with about 120 new applications for new research permits in geothermal resources suitable for power generation, cogeneration and district heating. After this initial rush, only a few proposed projects completed the surface exploration and in most cases the Environmental Impact Assessment (EIA) procedure required for the mining lease is still ongoing.

This slowdown is partly due to the change in the electricity market and the support for renewable energies. In 2013 “Green Certificates” were replaced by an “Incentive Fee” similar to an all-inclusive fee decreased by the zonal price of energy to which additional premiums can be added. The value of the net kWh generated from new or recent geothermal power plants passed from about 13.7 Eurocent/kWh awarded with “Green Certificates” to 9.9 or 8.5 Eurocent/kWh with the new “Incentive Fee”, for units with an installed capacity under or above 20 MWe, respectively (Conti et al., 2016).

Another reason for the slow development of new geothermal projects is the issue of social acceptability for some local communities who are concerned by environmental issues. The first formal national guidelines for defining environmental features related to geothermal development were released in July 2016, and described the best practice to be followed in the most important phases of a geothermal project, in particular for those related to electrical power generation and requiring the drilling of deep wells (MISE-MATTM, 2016).

In this paper, we outline the environmental aspects of geothermal development in Italy, the associated risks, the reference data and the adapted form of mitigation and/or abatement measures. We focus on the potential impact related to the development of geothermal power production, since

for other applications the potential impact is negligible or, in any case, a subset of those here discussed. Indeed, geothermal fluids used for power production are, both in terms of chemical composition, temperature and pressure, those requiring the highest level of safety procedures in their management. In addition, while there are considerable reliable data for geothermal power production, little is available for other applications.

All phases of a geothermal project can potentially produce environmental impacts, including exploration e.g., active seismic exploration methods. However, we will focus only on those phases specifically related to geothermal plant development. The main activities causing an environmental impact are related to:

- Building of access roads and drilling pads
- Well drilling, well repairs, and well testing
- Laying of pipelines, electric power transformation and transmission lines
- Plant construction and installation of equipment
- Power plant commissioning and operation
- Decommissioning of facilities

Before giving a detailed description of the environmental aspects, we first summarize the power production technologies used in Italy, thereby introducing some of the most technical terms which will then be used in the following sections.

2. Electricity generation technologies

Almost all the power plants in operation in Larderello-Travale and Mt. Amiata are based on direct cycle or flash cycle technologies, depending on the nature of available geothermal fluid which in these areas can be superheated steam, saturated steam or two-phase fluid with an NCG (Non-Condensable Gases) content of about 2-10% wt.

In the direct cycle technology, the steam (see Figure 2) comes from production wells or flash stage, and is fed directly into a steam turbine. After the steam expansion, where power is produced, the steam is condensed in a mixer condenser through the use of cooling water. The condensed steam and the cooling water are then fed to a wet cooling tower (normally three cells are used for a standard 20MWe unit) where the water is cooled and the condensed steam is partially stripped and emitted with the heated air (about 50-70% of the inlet flow). Stripped condensed steam and water drops of various dimensions (known as *drift*) are then released into the atmosphere, and contain components already present in the original geothermal fluid. The most recent cooling towers are equipped with a drift eliminator, which guarantees drift emissions lower than 0.1 m³/h. The remaining part of condensed steam flow (about 30-50%) is injected into the reservoir. In the mixer condenser, the gas is separated from the condensed steam and is fed, through a gas extractor, to an abatement system. The first abatement system was installed in Italy in 2002 (Baldacci, 2004).

Various technologies are available for abating hydrogen sulphide, both upstream and downstream of turbines, as described by Rodriguez et al. (2014). In all the power plants in operation in Italy, NCG is treated downstream of the turbine and of the condenser with AMIS systems that abate both hydrogen sulphide and mercury (Sabatelli et al., 2009). The main steps of the AMIS process are: i) abatement of mercury achieved by specific sorbents such selenium or activated carbon; ii) abatement of hydrogen sulphide by catalytic oxidation to SO₂ followed by a wet scrubbing with an alkaline solution (usually geothermal fluid containing NH₃ or with the addition of NaOH) (Baldacci, 2004).

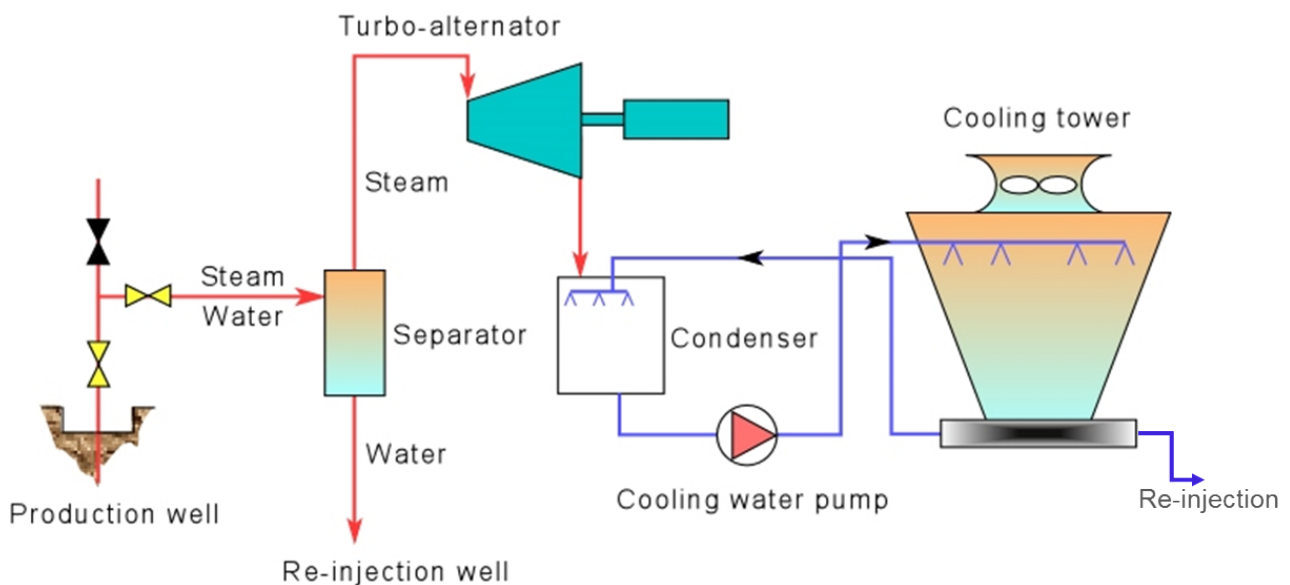


Figure 2 – Direct cycle technology scheme.

The first binary power plant in operation in Italy (Gruppo Binario Bagnore 3, Mt. Amiata – 1 MWe) was set up in 2012, and is fed with steam coming from a secondary flash. In the binary technology (see Figure 3) the geothermal energy is transferred through a heat exchanger to a secondary fluid that works in a closed ORC (Organic Rankine Cycle). The heat transferred from the geothermal fluid vaporizes the secondary fluid, characterized by a low boiling point and high density, which is fed to a turbo-expander to produce power. Binary plants in Italy are based on a subcritical ORC technology and use n-pentane as the working fluid.

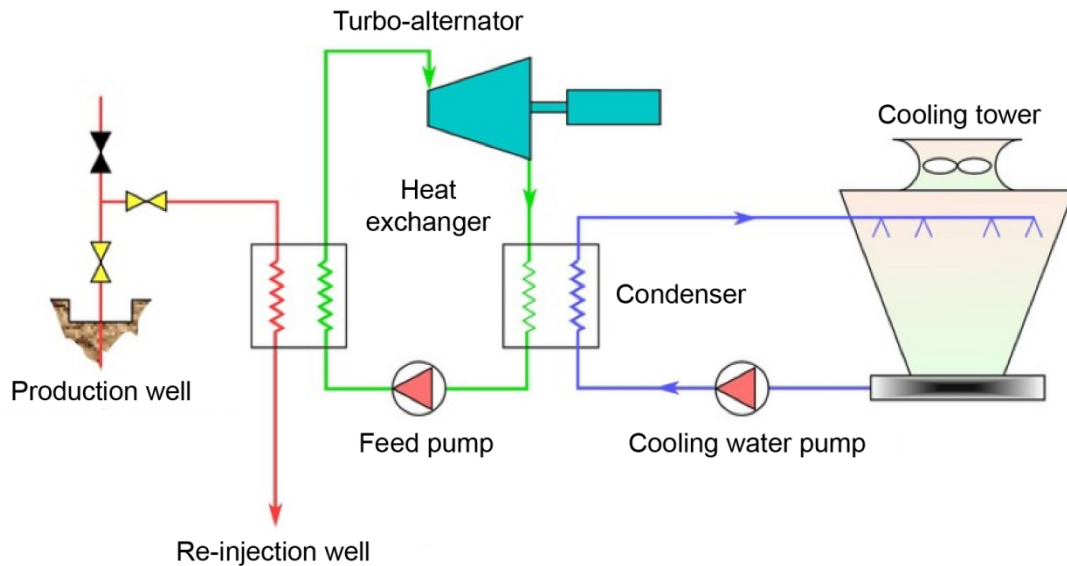


Figure 3 - Binary cycle technology scheme

An innovative biomass and geothermal hybrid plant became operational in 2015 (Cornia 2). The existing geothermal plant was boosted with a 16 MWth steam superheater powered with locally-sourced virgin forest biomass produced within a radius of 70 km from the plant. Thanks to both the greater enthalpy of the steam, whose temperature was raised from 150-160°C to 370-380°C, and the enhanced efficiency of the cycle, the net capacity and the power production increased of 6 MWe and 37 GWh, respectively. This plant represents a major technological innovation with virtually no impact on the environment, as it supplements an existing industrial site maintaining the total renewability of the resource and the cycle.

3. Environmental impacts and best practices

There are various methods to classify the environmental effects of geothermal projects. In this review, we describe the environmental aspects in relation to the matrices (air, water, ground) potentially affected by geothermal development. For each of the most critical sources of potential impact, we provide a brief description, related data, the adopted mitigation and abatement measures, and related regulations and provisions. Environmental aspects are regulated by European, Italian and regional legislation; Italian regional governments are supported, by law, by a regional environmental agency (Agenzia Regionale per la Protezione Ambientale, ARPA) aimed at enforcing environmental legislation, according to the guidance of the regional authority.

We will refer in particular to Tuscany, and to the regional government of Tuscany, and the environmental agency (ARPAT), since Larderello and Mt. Amiata geothermal power plants, which are by far the largest geothermal facilities in Italy, are both located in Tuscany. They make use of very high temperature fluids, hence have the greatest potential impact on the environment. They are also the most regulated, controlled and monitored, producing a wealth of publicly available data.

Tuscany represents an important reference for other regions and facilities in Italy, for which data are fragmented or unavailable.

3.1. Atmospheric emissions and monitoring

Air quality in geothermal areas

High temperature geothermal fluids usually contain gas in variable quantities, ranging from 2% to 10% in weight, composed of CO₂, H₂S, H₂, CH₄ and other trace elements as Hg, As, B, Rn, Sb and NH₃. Solid particles or water soluble gases may be included in aerosol particles (drift) emitted from cooling towers, deposited on soil and washed out by rain.

NO_x, SO₂ and primary particulate matter (PM) are not directly emitted by geothermal plants; secondary PM may form from the oxidation of H₂S and NH₃. For conventional geothermal plants not equipped with abatement systems, SO₂ and NO_x are estimated to be about 1% of the emissions from fossil fuel power plants of equal size (Matek, 2013).

Gas concentrations in geothermal fluid vary according to the reservoir features. CO₂ and H₂S, the most abundant gases, account for about 95% and 1-2% max of the NCG contained in geothermal fluids, respectively. NH₃ and H₃BO₃, which are very soluble in water, are mainly found in the aqueous phase, and are transported into the atmosphere through air stripping (NH₃) and drift (NH₃ and H₃BO₃) from the cooling towers.

The dispersion of gas emissions depends on the meteorological conditions, on the orography, on the height of the emission points, and the temperature of the gas. The non-condensable gases are mainly emitted downstream of the condenser, after AMIS abatement, and at the outlet of the cooling towers. If an efficient gathering system is not available in order to redirect the geothermal fluid to another power plant, significant emissions may also occur during well drilling (discharge and degassing) and during plant shut-down (free steam discharge).

Geothermal plants use fluids with different compositions and adopt different technologies for the exploitation, consequently the calculation of emission factors found in the literature is not standardized and emissions from individual plants may vary considerably from average values. Moreover, in estimating the emissions, we must consider that geothermal gases may also be naturally emitted from soil. Correctly estimating a geothermal power plants emission factor entails taking into account the natural emission factor from the soil, i.e. before industrial development (Holm et al., 2012; Shutz et al., 2013). As stated by the Intergovernmental Panel on Climate Change represented by Goldstein et al. (2011) “... *varying quantities of GHGs, which are usually small... originate from naturally sourced CO₂ fluxes that would eventually be released into the atmosphere through natural surface venting. The exploitation of geothermal energy does not ultimately create any additional CO₂ from the subsurface, since there is no combustion process, though the rate of natural emissions can be altered by geothermal production depending on the plant configuration*”.

Air quality in geothermal areas (irrespective of whether they are volcanic) depends on the geothermal fluid content, and is related both to geothermal plants and natural manifestations. Baseline air quality monitoring (including dispersion models) around geothermal power plants should be undertaken to assess background level of the air in order to differentiate between natural environmental conditions and impacts related to geothermal power production.

The public air quality monitoring network for geothermal power plants in Tuscany includes a fixed unit (located in Pomarance, close to the town of Larderello, and belonging to the network of monitoring stations coordinated by regional authorities), which monitors H₂S, O₃, NO₂ and PM₁₀, plus two mobile laboratories. Enel Green Power manages 18 air quality monitoring fixed units located in Larderello and Mt. Amiata areas, which monitor H₂S. Data from control units are checked, validated and published by ARPAT (e.g. ARPAT, 2016a).

Here we describe the characteristics of the main pollutants, reporting data on emission factors in Italy (Tuscany) and, for comparison, data from the USA, Iceland and New Zealand (Table 1).

Emission factor	Larderello-Travale average	Mt. Amiata average	Total average	Total Min-Max	Other countries
CO ₂ kg/MWh	314.49 (1)	852.29 (1)	372.57 (1)	183.5-531.5 (1)	180 Flash steam - USA (c) 245 USA, California-Coso (e) 45 USA, California-The Geysers (e) 107 USA, California (e) 26-181 Iceland (d) 34 Iceland (e)
	309 (5)	497 (4) 508 (5)	333 (5)	76-813 (5)	104.4 New Zealand (e)
CH ₄ kg/MWh	1.43 (3)	11.9 (3)	2.39 (5)	1.3-6.0 (1)	0.75 USA (a)
	1.22 (5)	8.41 (5)			0.85 New Zealand (b) 18.3 New Zealand (e)

H ₂ S kg/MWh	2.93 (1)	4.40 (1)	3.09 (1)	1.1-3.2 (1)	0.085 USA (a)
	0.96 (5)	0.81 (5)	0.96 (5)	0.3-3.2 (2) 0.27-2.74 (5)	
Hg g/MWh	0.16 (1)	1.34 (1)	0.29 (1)	0.06-0.8 (2)	
	0.08 (5)	0.1 (5)	0.1 (5)	0.02-0.47 (5)	
As g/MWh	0.09 (1)	0.15 (1)	0.09 (1)	0.02-0.11 (1)	
	0.09 (5)	0.07 (5)	0.08 (5)	0.01-0.38 (5)	
NH ₃ kg/MWh	0.46-0.70 (1*)	3.27-5.53 (1*)	0.77 (1)	0.16-2.67 (5)	0.06 - USA (a)
	0.53 (5)	0.7 (5)	0.7 (5)		
Emission Factors in salt dissolved in the drift					
As g/MWh				0.0027 - 0.081 (1)	
Hg g/MWh				7 x 10 ⁻⁵ - 8 x 10 ⁻⁴ (1)	
NH ₃ g/MWh				21 – 100 (1)	
H ₃ BO ₃ g/MWh				5.2- 55 (1)	

Table 1: Emission factors (units per year) in Italy and abroad.

Italian data from (1) DGR 344, 2010; (2) ARPAT, 2014; (3) ARPAT, 2017 (where available, CH₄ values were calculated from emission fluxes and average MWe); (4) Bravi and Basosi, 2014 (Four geothermal plants monitored in 2002-2009); (5) 4) Enel Green Power official reports on emission control, transmitted to ARPAT, referred to 2016 emission measurements. (*) In Reference (1), maximum emission factors are conservative and derived from concentrations in the geothermal fluid at the inlet of the plant.

In USA, Iceland and New Zealand: (a) Bloomfield et al., 2003; (b) Bayer et al., 2013; (c) Holm, 2012; (d) Ármannsson et al., 2005; (e): Fridriksson et al., 2017.

The main non-condensable gas emitted is carbon dioxide (CO₂), with emission factors that vary considerably (see Table 1). Only a few plants, corresponding to less than 3% of the total MW produced, emit more than 500 kg/MWe of CO₂, while 63% emit less than 100 kg/MWe, with a weighted average of 122 kg/MWe (Bertani and Thain, 2002, and recent data from Enel Green Power).

The high emission factors from geothermal plants in Italy, in particular those in the Mt. Amiata area, are due to the naturally high concentration of CO₂ in the geothermal fluids. Both the composition of the reservoir rocks, which are rich in carbonates and phyllites, and the shallow magmatic processes contribute to the natural enrichment of carbon dioxide. In addition, given that CO₂ has a high fugacity,

it is naturally emitted by the soil and by natural thermal/volcanic manifestations (Chiodini et al., 1998; Chiodini et al., 2005; Werner and Cardellini, 2006).

In Italy, this natural flow was not measured before the industrial development of geothermal plants, since development began at a time when environmental effects were not monitored. Thus, today it is only possible to perform *a posteriori* and partial evaluations. Mt. Amiata area is characterized by a high CO₂-rich gas emission from natural manifestation (Tassi et al., 2009). Present-day natural discharges of CO₂ through soils in Amiata are less than the CO₂ discharged from geothermal plants: 2.1 10⁹ mol a⁻¹ and 5.8 10⁹ mol a⁻¹, respectively (Froncini et al., 2009). Given the reported reduction of natural manifestation and CO₂ degassing in Larderello (Bertani and Thain, 2002) and Amiata (Froncini et al., 2009) subsequent to the geothermal development, the amount of emissions referred to industrial plants is probably overestimated due also to the fact that some natural emission in the geothermal area are not already identified. For example, if we could establish that the original discharge of CO₂ in Mt. Amiata area was 2.8 10⁹ mol a⁻¹ before industrial development (as indirectly estimated by Froncini et al., 2009), and considering that the current discharge is about 7.9 (2.1+5.8) 10⁹ mol a⁻¹, the correct value to attribute to power plants would be 5.1 10⁹ mol a⁻¹, and not 5.8 10⁹ mol a⁻¹. Given that a measured pre-industrial discharge value is not available, speculation is unavoidable.

Hydrogen sulphide (H₂S) is the most abundant non-condensable gas released from a geothermal plant after CO₂. Formed in anaerobic environments and unstable in oxidizing environments, it is found in volcanic emissions, hydrothermal manifestations and geothermal fluids, and wherever anaerobic decomposition of organic substances occurs. Although it is not possible to fix an exact lower threshold, the World Health Organization (WHO) proposed the reference value of 15 mg/m³ as the Lowest Observed Adverse Effect Level (LOAEL), in terms of the effects on human health (e.g. eye irritation WHO, 2000). H₂S forms a secondary particulate, and it can be washed by rain or it can be oxidized to SO₂. Nevertheless, SO₂ emission factors are negligible compared to those of fuel oil power plants.

In Tuscany, hydrogen sulphide is emitted from geothermal plants, as natural manifestations from hydrothermal water and as endogenous gas from soil. Based on the most recent data provided by Enel Green Power, the geothermal field of Mt. Amiata has the lowest emission factor (see Table 1). Methane (CH₄) is present in the non-condensable gas fraction of geothermal fluids and naturally emitted from soil in geothermal areas, with a concentration ranging from a few ppmv to a few percentage units. CH₄ is an ozone-depleting gas with a very high Global Warming Potential, estimated to be more than 20 times higher than CO₂. Emission factors in Italy are higher but comparable to those reported for other countries. Emission factors for Amiata are higher than those in Larderello (see Table 1).

Ammonia (NH₃) forms ammonium hydroxide with water vapour and contributes to secondary particulate with anhydrides. When oxidized, it contributes to soil acidification. Ammonia emissions from geothermal plants in Tuscany represent about 30 to 40% of the total emissions (DGR 344, 2010). The ammonia emission factors reported in Table 1 are the sum of both the gaseous and the aqueous emissions in the drift.

Arsenic (As) is an extremely toxic and carcinogenic substance, found in many organic and inorganic compounds, and in different oxidation states due to its high reactivity. Arsenic emission into the atmosphere is frequent during volcanic eruptions, but rare in geothermal manifestation. Wherever present in geothermal fluids, arsenic remains in the aqueous phase and can be easily reinjected. Small and very variable amounts may be emitted by the drift in cooling towers, thus requiring an evaluation in each well (Fowler, 1983). Emission factors of arsenic¹ from drift in Tuscany are reported in Table 1.

Mercury (Hg) is found in mineral form (cinnabar) or in very small metal droplets. Since it is volatile, mercury vapour can be transported into the atmosphere and transformed into the very toxic methylmercury in animal organisms, also reaching the human food chain. Mercury is emitted from carbon power plants and waste incinerators, and can be found in some geothermal fluids, especially in mining areas, e.g. The Geysers (California, USA) and Mt. Amiata (Tuscany, Italy). Where present, mercury is emitted both in NCG and, as salt, it is dissolved in the drift. The drift drops are deposited on soil in the vicinity of plants, whereas NCG may be transported several kilometres away and absorbed in aerosol particles and then inhaled.

Boron is found in evaporitic deposits from hydrothermal water as salt (borate). Boron is toxic only when ingested, while its presence in soil is necessary for plants growth. Boric acid (H₃BO₃) is contained in the drift emitted from cooling towers. When combined with ammonia, ammonium borate is deposited on the plants walls. The boron emission factor in the drift was once recorded in Tuscany (Table 1), but more recent data are not available and the boron emission factor is probably lower thanks to the installation of innovative drift eliminators in the wet cooling towers of the new or the retrofitted geothermal plants.

Emissions and air quality regulations

Regarding the substances emitted by geothermal plants, EU and Italian regulations establish air quality standards only for mercury and arsenic, and define Emission Limit Values as mass flow or as a combination of mass flow and concentration. Emissions from geothermal plants in Italy are fully compliant with these Emission Limit Values. In the absence of regulatory standards for other contaminants, reference values established by international organizations (e.g. WHO) or other authorities in this field (e.g. American Conference of Governmental Industrial Hygienists ACGIH) can

¹ The difference between total arsenic emission factor and drift arsenic emission factor (reported in Table 1), is due to the different order of magnitude of the detection limits of the two techniques adopted to measure total arsenic emission and drift arsenic emission.

be taken as good practice by regional authorities. Table 2 shows the reference values adopted in Tuscany and the main international references.

In order to reduce the release of pollutants into the atmosphere, the regional government in Tuscany has: i) defined reference emission thresholds, in line with technological innovations; ii) introduced new on-line emission monitoring systems and improved existing ones for air quality; iii) funded research and testing of new abatement technologies for other pollutants. Lower emission limits have been defined in Tuscany for the authorization of new or retrofitted geothermal plants, taking into account the technological improvements achieved by abatement technology. The current legislation thresholds and reference data are summarized in Table 2 (DGR 344, 2010). More recently, the regional government in Tuscany has prescribed the installation of abatement systems for reducing ammonia by at least 75% (ARPAT, 2017).

<i>Parameter</i>	<i>Concentration</i>	<i>Reference</i>
<i>Hydrogen Sulphide (H₂S)</i>	150 µg/m ³ daily average	(1)
	100 µg/m ³ for 1-14 days (average over the period)	(2)
	20 µg/m ³ up to 90 days (average over the period)	(2)
<i>Arsenic (As)</i>	6 ng/m ³ yearly average	Target value from EC directive 2004/107/CE of 18/12/2004 and D. Lgs. 152/2007
<i>Mercury (Hg)</i>	0.2 µg/m ³	(3) December 2007. Reference year 2001
<i>Boron (B)</i>	20 µg/m ³ daily average	Confidence interval 100 with respect to TLV-TWA of 2 mg/m ³ reported in (4) (inorganic boron)
	10 µg/m ³ > for 1-14 days (average over the period)	(3) December 2007
<i>Ammonia (NH₃)</i>	170 µg/m ³ daily average	Confidence interval 100 with respect to TLV-TWA of 17 mg/m ³ reported in (4) (ammonia)
	70 µg/m ³ > for 1-14 days (average over the period)	(3) Reference year 2004
<i>Antimonium (Sb)</i>	5 µg/m ³ daily average	Confidence interval 100 with respect to TLV-TWA of 0.5 mg/m ³ reported in (4) (antimonium)

TLV-TWA = Time Weighted Average.

Ref: (1) WHO, 2000; (2) WHO – IPCS; (3) MRL Minimal Risk Level (ATSDR); (4) ACGIH, 2006.

Table 2: Concentration thresholds adopted in Tuscany (from DGR 344/2010).

Recent national guidelines (MISE-MATTM, 2016) stipulate that authorizations for new plants are subordinated to the definition of predictive models for emission effects and the planning of monitoring and abatement measures.

Mitigation of emissions

The best technology for reducing air emission depends on the type, size and estimated lifetime of the plant and on the concentration of pollutants in the fluid. In Italy, partial reinjection of fluids, excluding NCG, and the adoption of abatement systems are common practice.

Power production from geothermal fluids with high gas content achieves a low emission factor either using abatement technologies, as is the case in the plants in Italy, and by gas reinjection, as outlined in some proposed geothermal projects and currently done in some areas of Iceland (Matter et al., 2016). Currently, in the world there is no total reinjection geothermal power plant fed with geothermal fluid characterized by NCG content > 1% wt. Gas reinjection technologies, which are debated in Italy and proposed as “zero emission technologies”, have not been adopted by Enel Green Power given their high safety and environmental risks due both to potential gas breakthrough phenomena occurring if the reinjected gas is not properly mineralized and to the high pressure of pipeline and equipment necessary for gas reinjection. Differently from Iceland, where gases are partially injected in highly reactive basaltic rocks rich of calcium, magnesium and iron, Italian reservoir’s rock composition does not guarantee the rapid formation of carbonate minerals. The risk caused by gas reinjection would further increase by adopting binary instead of flash plants, because the high-pressure enhances the risk of fugitive emissions of the secondary fluid utilised (typically hydrocarbons and heavy fuel oils characterized by a high global warming potential (Bayer et al., 2013)).

For abatement, the NCGs, mainly containing CO₂, H₂S and Hg, are separated downstream of the turbine condenser and are treated in abatement systems for H₂S and Hg (AMIS). Periodic maintenance of abatement systems and the adoption of a monitoring plan also help minimize emissions. Maintenance and monitoring are key steps in the implementation of an effective Environmental Management System, which is regarded as “best available technique” by the European Union² and enforced in the emission permits in Europe and, therefore, in Italy.

H₂S emission factors reported in Table 1 show a strong decrease after the installation of AMIS abatement plants. Figures 4 shows the decreasing trend in Tuscany in the yearly average values of hydrogen sulphide (H₂S) detected in 2010-2015, calculated from hourly concentrations (ARPAT,

² See the BREF documents (European Commission, 2003) enforcing the application of the European Directive 96/61, also known as the IPPC Directive for “Integrated Pollution Prevention and Control”, and the IPPC Reference document on monitoring.

2015 and 2017). When compared to the threshold air quality values for H₂S indicated by WHO (2000), which are 150 µg/m³ (24 h average), 100 µg/m³ (14 days) and 20 µg/m³ (90 days), these values are clearly safe.

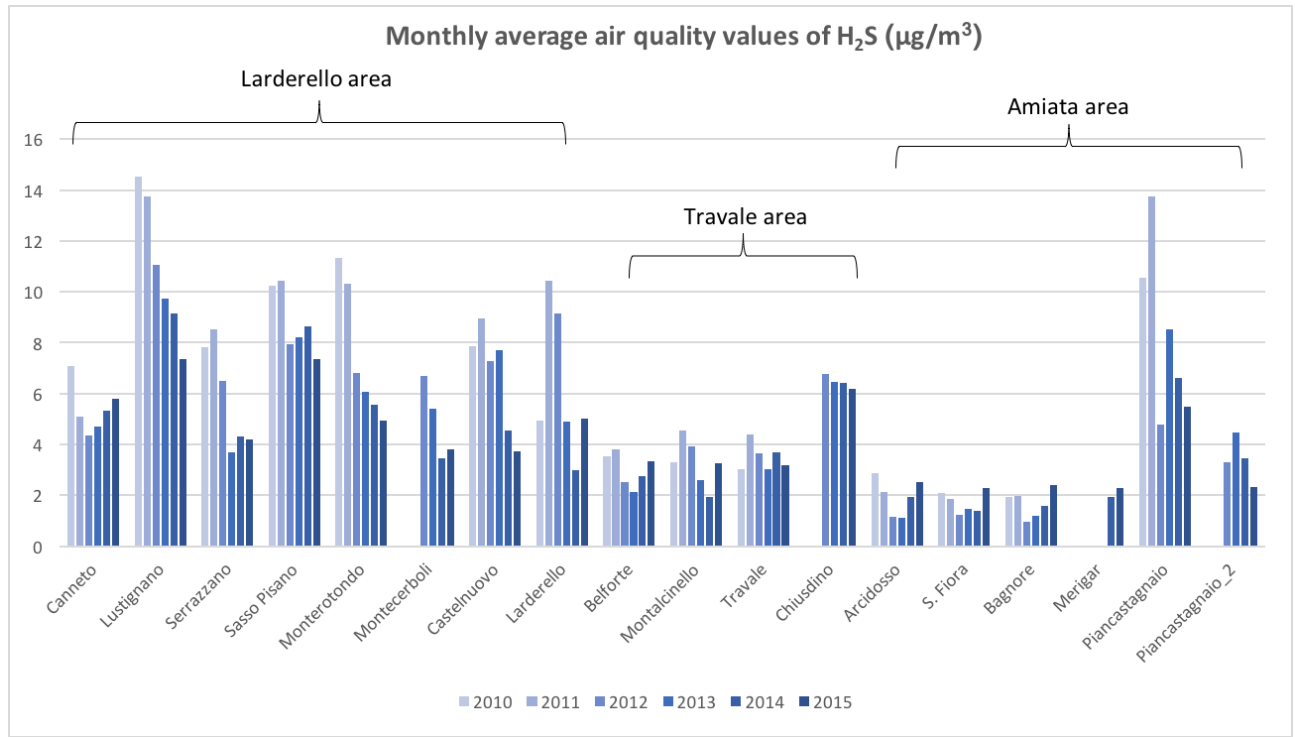


Figure 4 - Yearly average air quality values of H₂S recorded from 2010 to 2015 (ARPAT, 2015 and 2017).

Mercury removal in non-condensable gas is around 80-98%, and H₂S abatement is around 90-99% (ARPAT, 2015). Thanks to the installation in some geothermal plants of Mt. Amiata of a dedicated abatement process for ammonia, which is able to reduce emissions by up to 80-90%, ammonia emission factors range have been considerably reduced (see Table 1). The abatement is achieved by forming ammonium sulphate, which is not stripped by the air in the cooling tower. Table 3 shows the abatement rates achieved in some power plants characterized by high ammonia content (Bagnore 3 and Bagnore 4 power plants).

Name	Date	NH₃ input (kg/h)	NH₃ output (kg/h)	NH₃ abatement (%)
<i>Bagnore 4 Grp1</i>	March 2015	176.1	27.1	84.6
<i>Bagnore 4 Grp2</i>	March 2015	185	24	87
<i>Bagnore 3</i>	March 2015	158	38.5	75.6

Table 3 - Ammonia abatement from a survey carried out in 2015 (ARPAT, 2017)

Aerosol emissions and soluble pollutants are reduced using drift eliminators, which may reduce the drops of condensate and the mass flow of the substances dissolved in the condensate (mercury and hydrogen sulphide residues but also arsenic, ammonia and boron, if present in the geothermal fluid). The drift eliminators installed in the most recent and in the retrofitted cooling towers ensure drift emissions lower than 0.002% of the total flow rate entering the cooling tower (about 370 l/h for the three 20 MWe units of Bagnore 3 and 4 power plants), in accordance with regional government regulations (e.g. Tuscany RG, 2012). These drift eliminators have also strongly reduced arsenic emissions (see Table 1).

3.2. Noise

Noise can be produced in the three main sections of a geothermal production system: production and reinjection wells, pipelines to plant and geothermal plants themselves. In production and reinjection wells, noise is produced during the initial setup and construction of drilling site due to truck traffic, by drilling operations and by well tests after drilling.

Regulations

Noise production is classified as a form of pollution by Italian law which defines the maximum allowed noise levels, how to handle acoustic pollution, the evaluation of sound sources etc.

The level of noise allowed is regulated according to the local area and its usage, and different levels are set for night-time (22:00 pm to 6:00 am) and day-time (6:00 am to 22:00 pm). Six classes of land use and related admissible noise level are established. For each class, noise emission limit values are given together with emission levels values and quality standard levels as summarized in Table 4.

Territory classification		Emission Level Values dB(A)		Intake Level Values dB(A)		Quality Standard Values dB(A)	
CLASS		Day	Night	Day	Night	Day	Night
I	Areas with special protection: hospitals, schools, rural residential sites, parks etc.	45	35	50	40	47	37
II	Mainly residential areas, with commercial and industrial activities	50	40	55	45	52	42

III	Mixed residential and non-industrial production activities areas	55	45	60	50	57	47
IV	Intensively inhabited areas	60	50	65	55	62	52
V	Mostly industrial areas, scarcely inhabited	65	55	70	60	67	57
VI	Exclusively industrial areas	65	65	70	70	70	70

Table 4: Noise Limit Values in the environment (dB(A)) according to destination of sites

By law, each municipality must perform an acoustic characterization, i.e. mapping and ranking, of its local area according to the classification in Table 4.

Authorizations for temporary activities that overcome the noise limits can be requested to local municipalities.

Mitigation measures

Noise reduction technologies are widely applied in Italy, e.g. sound barriers, sound shields on engines, and low noise equipment for well testing. Drilling, which is a temporary activity, is often performed in areas with few inhabitants and noise at receptors is well below the limits set for those areas. Pipelines are essentially non-acoustic impact equipment, including the maintenance work.

The acoustic impact during geothermal power plant construction is evaluated in the EIA required by the authorization process. The detailed description of the construction phases provided by EIA takes in account the noise due to transportation of materials, the plant construction and test phases.

After plant construction, all the technologies adopted in geothermal power plants in Italy, reached by continuous improvement of plant equipment performance, keep the noise level below the most restrictive CLASS I standards. A substantial noise reduction has been obtained by the thermal insulation of turbine and the soundproof cages around the turbines and alternators.

Cooling towers tend to produce the loudest noise. According to Enel Green Power internal reports, the acoustic impact has been reduced from 90 to 75 dBa by placing carpets on the water surface level, using wood for construction, soundproofing fan motors, and using purpose-built vertical axis motors.

Thanks to the above-mentioned improvements, the geothermal power plants performances in Italy are today compliant with the most restrictive noise emission levels (e.g. Enel Green Power EIA, 2011).

3.3. Surface water and groundwater interference

Water is increasingly a key resource. If the right criteria for plant construction and operation are not applied, there can be a negative impact on water quality, quantity and underground circulation.

Regulations

The reference law for the protection of water in Italy is Part Three, Section II (Environmental regulations - Soil protection and the fight against desertification, protection of waters against pollution and management of water resources) of D. Lgs. 152/2006 and subsequent amendments. This section of the regulations aims to ensure the sustainable use of water resources and establishes the methods for water monitoring and use, as well as the procedures for obtaining permission to discharge into sewers, groundwater and surface water. D. Lgs. 152/2006 implements European Directive 2000/60 for monitoring and classifying the water quality, and makes regional authorities responsible for planning and monitoring of surface and underground water quality and quantity. Further instructions related to monitoring procedures in Italy are defined in recent guidelines (MISE-MATTM, 2016). They include monitoring techniques, suitable locations for monitoring stations, and the frequency of controls.

Water use and consumption

All geothermal power plants use a considerable amount of geothermal fluid. After power generation and condensation, these fluids are available for other uses before being reinjected. Water is required during the drilling and construction phases. If geothermal fluid is not available, fresh water is needed for the drilling mud and the cement used to stabilize the well's walls. Also the cement for pipelines and plant requires some water during plant construction. Since water is about 10% of the weight of cement, the estimated amount of water required for cementing 1 km of pipelines is 10-15 m³.

No additional water is needed during the operation of power plants. For example, to compensate for the water (constituted by condensed steam stripped by air) lost by evaporation and dispersion of the drift, water-cooling towers use condensed vapour coming from the condenser as make-up, thereby avoiding consumption of fresh water.

Surface and underground water pollution

Geothermal fluid contains a wide range of dissolved ions in its liquid phase, such as Na, K, Ca, B, Li, As, F, Mg, Si, Rb, Sb, Sr, chlorides, bicarbonates and sulphates. Super-heated steam contains mainly boric acid chlorides and bicarbonates and tiny amount of As and Hg. Both the naturally-occurring surface manifestations (putzze, mineralization, etc.) and industrial geothermal exploitation might affect the quality of surface water close to geothermal resources.

Geothermal operation may cause aquifer contamination through i) accidents during well drilling; ii) small but continuous spills in the pipelines, in the casing of the wells and in other parts of the geothermal power plant; and iii) accidental spills of mud and geothermal fluid temporarily stored in

tanks prior to reinjection. Well-casing failure, pipeline leakage, and other surface spills can be possible pathways for the contamination of surface and groundwater. Furthermore, the drift coming from cooling towers, once deposited in the soil near the power plant, can be leached, contributing to the contamination of soil, water and sediments. The deeper the ground circulation, the harder it is to identify possible effects on the quality of water (Benelli et al., 2008).

Contamination can be avoided by following the right procedures for drilling, and for operating and maintaining the facilities. The MISE-MATTM (2016) guidelines detail the correct operations (e.g. well blow-out prevention, cementing procedures, waste disposal) and material (mud, cement, casing) to be used in order to avoid pollution to the soil and underground water. Monitoring of soils and groundwater quality, which is also required in the guidelines, has been a key policy imposed by the regional government in Tuscany for many years.

For the authorization of operations at a geothermal plant, the water quality of surface and deep fluids, including springs, is monitored in Tuscany in order to establish the potential contamination of soil and of drinkable aquifer. Such contamination has been a primary concern in Mt. Amiata.

There are two geothermal reservoirs in the sedimentary and metamorphic units below the volcanic edifice of the extinct Amiata volcano. The volcanic edifice hosts the main drinkable aquifer that serves a large area located between southern Tuscany and northern Latium, and the possibility of groundwater contamination has been discussed both at a political and scientific level. Much of the scientific discussion is related to geological aspects, as evidenced by the comment of Barazzuoli et al. (2015) to an original paper by Borgia et al. (2014). Different geological models may or may not involve geological and hydraulic contact between the units hosting the drinkable aquifer and the geothermal reservoirs, with consequent different roles played by underground pressure changes induced by geothermal production. A key issue raised by local opposition to geothermal development in the area is the hypothetical contamination of the aquifer by the ascent of geothermal fluids (see the following section for more details). The level of arsenic in the drinking water is a particular concern.

In 2007 the regional government in Tuscany commissioned a study to identify the risk of contamination in Mt. Amiata geothermal area. The resulting report ruled out any chemical contamination between geothermal fluids and drinkable groundwater, and found that there was no hydraulic connection between the superficial and geothermal aquifers (University of Siena, 2008). The authors concluded that the arsenic concentrations measured in the groundwater, as well as the concentrations of antimony, boron, mercury and sulphur measured in soil and water samples around the geothermal areas, which fall within the range of natural variability in the local geochemical background, is essentially related to the metallogenic history of Mt. Amiata (known for its cinnabar mines). Only a limited and locally circumscribed increase in antimony and mercury in the soil around the power plants was attributed to geothermal development. The amount of these same elements measured in the river water samples were found comparable with those present in non-contaminated

water. Also the most recent monitoring of shallow water, spring water and deep water ruled out any chemical contamination of Mt. Amiata's drinkable water aquifer by geothermal fluids (ARPAT, 2016b).

The chemical-physical monitoring of wells and springs in Mt. Amiata has also revealed a decrease in the concentrations of boron and arsenic (2013-2014 reference years, ARPAT, 2016c). ARPAT suggests a close link between the past increase in arsenic concentrations in water and the regional water deficit in the years 2004-2005, 2008 and 2012, resulting from minimum rainfalls in 2003, 2007 and 2011.

Interference of groundwater reservoirs

Understanding the underground fluid circulation is complex, especially when there are few wells and there is little direct information. Hydraulic tests performed in the available wells, permeability characterization and hydrogeological numerical modelling are the main tools of an efficient and sustainable geothermal management. The effect of water withdrawal from geothermal reservoirs can be largely compensated by reinjection, i.e. injecting geothermal fluids into the geothermal reservoir. Although such reinjection is common in Italy, the geothermal fluid is not totally reinjected, due to geothermal fluid losses and to the amount of non-condensable gases. Accurate designs for reinjection, using predictive models on the evolution of the reservoir, and monitoring are required in order to take corrective actions.

An important consequence of the mass losses in liquid-dominated systems is often the occurrence of two phases (steam and liquid) in the upper part of the reservoir, close to the production area. If the depletion of the reservoir continues, the size of this phenomenon increases, whereas pressure decreases. In Italy, reservoir pressure losses have been kept to a minimum through careful management and reinjection (Cappetti et al., 1995; Kaya et al., 2011).

A hypothetical reduction of the water in the potable aquifer due to the geothermal exploitation has also been hotly debated in the Mt. Amiata area but with no definitive answer (Borzoni et al., 2014). As it is often the case, the main problem arises from the lack of sufficient information regarding the hydrogeological situation prior to the exploitation of the geothermal resource.

The regional government in Tuscany is funding research and monitoring, and there are now six piezometers installed in collaboration with Enel Green Power which access the potable aquifer, all equipped with automatic probes that monitor and register water level and conductivity in real time. Four of them are also equipped with automatic sampling devices. This continuous monitoring aims to reveal the hydraulic parameters of the freshwater resource and establish an exact correlation between the availability of drinkable water and meteoric inflow. The first piezometer was installed in 2010 and several years of observation are still needed in order to provide definite evidence.

3.4. Land Subsidence

Land subsidence, a vertical downward movement of ground surface, may result from natural processes, including tectonic movements and volcanic phenomena, or be induced by human activities. Fluid extraction from the underground, the most common anthropogenic cause of subsidence, leads to a change in the stress field in the reservoir and surrounding areas (pore-elastic and thermo-elastic deformation) thereby causing rock deformation. Depending on the thickness and mechanical properties of the rocks, this deformation can migrate to the surface producing vertical and/or horizontal ground movements and surface deformations (Narasimhan, 2013).

Land subsidence induced by the exploitation of geothermal field is well documented in the literature and has raised public interest. Geothermal power production worldwide is usually accompanied by some land subsidence, Wairakei geothermal field (New Zealand) being the most known and probably the best documented example (e.g. Allis et al., 2009).

Regulations

The first reference in Italian law related to mitigation of land subsidence phenomena is Law 183/1989. Today, the main reference is the D. Lgs.152/2006 and subsequent amendments to Part Three, aimed at ensuring the conservation and remediation of soil and subsoil, the hydrological restoration of the affected area through the prevention of instability phenomena, the safety of the risk situations, and combating desertification.

The 2016 guidelines for the utilization of geothermal resources at medium and high enthalpy describe procedures and protocols for monitoring and analysing the spatial-temporal evolution of seismicity, surface deformation and pore pressure (MISE-MATTM, 2016). They require the use of InSAR techniques complemented by GPS surveys during geothermal operations.

Mitigation measures

Monitoring, prediction and control are the three main means to mitigate the effects of subsidence in geothermal fields. By recording spatial changes and the temporal evolution of surface deformations (i.e. subsidence monitoring), information regarding subsurface modifications can be inferred. Various techniques for land subsidence evaluation and monitoring have been used around the world. Geometric levelling and GPS surveys with periodic and/or permanent networks are the traditional methods to study land subsidence in geothermal areas and are now being augmented by remote sensing and InSAR techniques. All these methods differ in terms of execution time, costs, and precision and accuracy.

In Italy, the levelling technique, which usually provides high precision, was the first to be used (Dini and Rossi, 1990; Ciulli et al., 2005). This technique suffers from relatively poor spatial resolution and the timing of the measures. This limitation can be partially remedied by GPS surveys, which can operate at night or in bad weather conditions, provided that the link between satellites is ensured, and which can measure real time 3D component displacements. GPS measurements provide information about levelling only at specific observation points. On the other hand, InSAR, a suite of satellite-based imaging techniques for measuring surface Earth deformations by comparing phase

information from images taken at different times, can quantify the ground deformations and its temporal evolution over wide areas with millimetre precision (Rosi and Agostini, 2013; Rosi et al., 2016).

In 1922-23 in the Larderello area changes in the ground elevation were monitored for the first time using a precise levelling network. In 1985-86, the measurements were repeated and defined an average subsidence rate of 26 mm/yr (Dini and Rossi, 1990). Periodic measurements after 1986 showed a decrease in subsidence rates, which decreased to maximum rates of 12 mm/yr between 1986 and 1993 (Dini et al., 1995). Recently, Rosi et al. (2016) mapped subsidence phenomena in Tuscany using InSAR and found that a broad area (129 km²) of Larderello is subject to subsidence with average ground downward velocities of about 10 mm/yr and peak velocities up to 30 mm/yr in the central part of the subsiding zone.

In the Travale-Radicondoli area monitoring of the vertical deformation began simultaneously with the industrial exploitation (early 1970s), using precise geometric levelling (Geri et al., 1982; Geri et al., 1985; Di Filippo et al., 1985; Di Filippo et al., 1995). GPS and EDM (Electronic Distance Measurement) methods were later applied (Beinat et al., 1995). Over a period of 30 years (1973-2003) the deformation measured gradually decreased from an initial rate of 23 mm/yr to 10 mm/yr (Ciulli et al., 2005).

InSAR data have shown that from 1993 to 2010 both Larderello and Travale-Radicondoli geothermal fields subsided with maximum annual rates of 29 and 15 mm/yr, respectively (Botteghi et al., 2015). The Mt. Amiata area has been monitored since 1980s using two precision levelling networks. As confirmed also by recent studies carried out using InSAR techniques, this area is not subject to subsidence (University of Siena, 2008).

Prediction is based on the numerical modelling of reservoir performance and requires the simulation of the complex interactions between heat and mass transfer processes and the reservoir properties (i.e., permeability and porosity), and of the geotechnical characteristics of rock. The types of models and software used to study geothermal land subsidence are well documented in the literature (Pritchett et al., 1976; Lippmann et al., 1977; Miller et al., 1980; Herd, 1985; Bodvarsson et al. 1994; Lawless et al., 2003; Yeh and O'Sullivan, 2007; O'Sullivan, 2010; Asadollahfardi et al., 2014; Koros et al., 2015).

In Italy, various numerical models have investigated the interactions between the geothermal field under exploitation and hydrogeology of the area, taking into account superheated steam production, and flow and heat transfer mechanisms (e.g., Della Vedova et al., 2008; Bellani and Gherardi, 2009; Barelli et al., 2010; Romagnoli et al., 2010). However, surface deformation was not taken into account by any of these models.

Injection and reinjection of fluids help in controlling and mitigating land subsidence in geothermal systems, since in many cases they compensate for mass deficit and pressure decline induced by fluid extraction. Injection and reinjection has proved so effective for pressure support, resource

sustainability and subsidence control that it is fast becoming an integral part of all sustainable and environmentally-friendly geothermal utilization (Axelsson, 2008; Diaz et al., 2016). In Italy, reinjection was first performed in the 1970s, and subsequently became a significant part of the exploitation strategy for geothermal areas (Razzano and Cei, 2015).

Infield reinjection in the shallow reservoir in Larderello field has produced, especially in the most depleted area (Valle Secolo), a significant increase in the steam flow rate and reservoir pressure. In the Travale-Radicondoli field, reinjection was applied for a few years to compensate for pressure decline and subsidence control (Di Filippo et al., 1995). Due to the high reservoir pressure (50–60 bar), geothermal fluids from Travale wells are transported to the Larderello area for reinjection (Romagnoli et al., 2015). In the Mt. Amiata area reinjection was used almost right from the beginning of exploitation (Capetti et al., 1995; Kaya et al. 2011).

In conclusion, it is not possible to establish a clear cause-effect relationship between reinjection and land subsidence in Tuscany, but there was a reduced rate of subsidence in the same years as the shallow infield reinjection in Larderello (Cappetti, 1995).

3.5. Induced Seismicity

The possible occurrence of earthquakes induced by geothermal activities, although relatively rare and generally of small magnitude, is understandably of public concern. In fact, fluid extraction and reinjection may generate stress field alteration in the subsurface as a result of pore pressure variation, isostatic disequilibrium, and poro- and thermo-elastic effects, and hence, in turn, produce seismicity (e.g. Grasso, 1992; Davis and Frohlich, 1993; Guha, 2000; McGarr et al., 2002; Majer et al., 2007; Suckale, 2009; Evans et al., 2012; US National Research Council, 2013; Ellsworth, 2013; Grünthal, 2014; McGarr, 2014; Astiz et al., 2014; Zang et al., 2014; Dahm et al., 2015). Over one hundred years of geothermal power production in Italy and many decades of production in many places in the world demonstrate that geothermal activities can be associated with induced seismicity³, usually of small magnitude (Evans et al., 2012; US National Research Council, 2013; Zang et al., 2014).

Guidelines and best practices

Understanding the basic physical processes that control the development of induced seismic event (e.g., Zoback, 2012; US National Research Council, 2013; Zang et al., 2014), the results of international research projects (e.g., GEISER Project <http://www.geiser-fp7.fr>), and the experience

³ Following McGarr et al. (2002), we should distinguish between: i) induced seismicity, in which the stress changes produced by a human activity is comparable with the ambient stress acting on a fault, and ii) triggered seismicity, in which the anthropogenic stress variation is only a small fraction of the natural tectonic stress field. Considering the difficulties in discriminating between « induced » and « triggered » seismic events, we use the term induced seismicity in a generic way for the two categories described above.

gained in several industrial initiatives (Kagel et al., 2007; Moeck et al., 2015) have led to the formulation of best practices. These practices help to assess, manage, and mitigate the potential seismic risk posed by some industrial activities, including geothermal. Five key practices involve: 1) detailed geological and seismotectonic studies to identify faults capable of generating damaging earthquakes, 2) technologies that maintain a balance between produced and reinjected fluid and minimize pore pressure changes at depth, 3) local microseismic monitoring networks, 4) operational protocols jointly defined by operators and public regulators (e.g., traffic light systems) to reduce or suspend activities if induced seismic events are detected, and 5) transparent and effective communication to achieve informed public acceptance.

These Best Practices have been implemented in Italy with the “Guidelines for monitoring seismicity, ground deformation and pore pressure in subsurface industrial activities”, developed by a working group established at the Italian Ministry of Economic Development within the Commission on Hydrocarbon and Mining Resources (CIRM Working Group, 2014). More recently, the “Guidelines for the usage of medium and high enthalpy geothermal resources” have further detailed the monitoring and operational procedures to be applied for geothermal activities (MISE-MATTM, 2016). Most of these best practices have actually been implemented by Enel Green Power since 1978, with 42 microseismic stations distributed in the Italian geothermal area, a data-room connected to the stations and real-time surveillance. All collected data are provided to the Tuscany RG and the Ministry of Economic Development every year.

Seismicity in geothermal areas in Italy

Seismic events in geothermal areas in Italy have been reported in the literature (see Table 6, Di Bucci et al., 2014, and references therein).

When analysing the possible link between the effects of geothermal exploitation and the onset of seismic events a distinction should be made between the specific hydraulic stimulations that are required to improve the reservoirs’ permeability in EGS (Enhanced/Engineered Geothermal Systems) projects, and the production technologies commonly applied in hydrothermal systems (and used in Italy).

In some hydraulic stimulation, seismic events with magnitudes higher than 3 have been observed (e.g., M_L^4 4.4 at Berlin in El Salvador or M_L 3.4 at Basilea; Majer et al., 2007; Zang et al., 2014). Hydraulic stimulations in Italy have been performed during short tests between the late 1970s and early 1980s to improve the permeability of the reservoirs of geothermal fields discovered in central Italy (i.e., Torre Alfina, Latera, and Cesano fields in the Latium region). Fluid injection in the subsurface was carried out in conjunction with the deployment of micro-seismic monitoring networks. The dataset collected during the hydraulic stimulations highlighted the occurrence of induced seismic

⁴ In this paper, local magnitude is designated as M_L , moment magnitude as M_w , whereas M refers to a generic unspecified magnitude in the original data source.

events, generally in sequences with magnitudes ranging from negative to about 2 and with maximum magnitude M_L 2 at Cesano, M_L 2.9 at Latera, and M_L 3.0 at Torre Alfina (Batini et al., 1980b; Cameli et al., 1983; Carabelli et al., 1984; Batini et al., 1990; Moia et al., 1993; Evans et al., 2012). These experiments also showed that the onset and the magnitude of induced seismic events can be correlated with the injected volumes and with the pressures applied. Geothermal projects in Italy today avoid any hard stimulation technologies, e.g. pumping of large volumes of fluid underground, thus minimizing risks of induced seismicity.

The seismic events associated with the standard fluid reinjection techniques used in Italian geothermal areas have a magnitude generally lower than 2-2.5 (Batini et al., 1980a; Batini et al., 1985; Batini et al., 1990; Moia et al., 1993). Table 6 shows that some seismic events of a slightly larger magnitude were recorded in geothermal areas in Tuscany and Latium. They are difficult to interpret due to the natural seismicity occurring in these areas (Castello et al., 2006; Rovida et al., 2011; ISIDe Working Group, 2016). For example, the Parametric Catalogue of Italian Earthquakes CPTI11 (Rovida et al., 2011), which provides homogeneous macroseismic and instrumental data and parameters for Italian earthquakes for over 1000 years from 1000-2006, reports significant earthquakes in western Tuscany (in 1414 with maximum intensity 8-9 and M_w 5.6), at Mt. Amiata (in 1919 with maximum intensity 8 and M_w 5.3) and Latera geothermal field (in 1882 with maximum intensity 6 and M_w 4.7).

In vapour-dominated systems the occurrence of induced earthquakes is very site-specific. For example, the induced seismicity, up to magnitudes M_L 4.6, in the vapour-dominated The Geysers field in the USA, was attributed, considering the very low reinjection pressure, to the thermal contraction of the hot reservoirs rocks generated by the reinjection of cold water, which may have activated mechanical discontinuities (US National Research Council, 2013) or to pore pressure variations and volumetric effects associated with the pronounced decline in reservoir pressure during the 30-year production history (Bromley and Majer, 2012). In the vapour-dominated Larderello-Travale geothermal field, the maximum magnitude of observed induced seismicity is significantly lower (M_L max 3.2; Evans et al., 2012). This different behaviour may be explained by the onset of reinjection operation at an early stage of the Larderello field exploitation, which limited pore pressure decline.

Power production from liquid-dominated geothermal systems, such as in Mt. Amiata and Latium geothermal areas, generally occurs with a substantial balance between the amounts of fluids produced and reinjected, which prevents pore pressure decline. In addition, produced and reinjected fluids usually show limited temperature differences, thus cooling effects are reduced. Consequently, the prerequisites for the development of induced seismicity is significantly weakened (US National Research Council, 2013). Accordingly, in liquid-dominated geothermal systems the observed induced seismicity is absent or, where detected, of small magnitude. Nonetheless, the seismicity of the liquid-dominated system of Mt. Amiata has been a matter of debate, and the earthquakes in 1983

(M_L 3.5) and 2000 (M_L 3.9) were considered as being induced in some studies and natural in others (Mucciarelli et al., 2001; Evans et al., 2012; Mazzoldi et al., 2015).

Geothermal Field	Year of the event	Maximum Magnitude (M_L)	Type	References	Comments
Larderello/ Travale	1978	3.2	Supposed	Batini et al. (1980a); Batini et al. (1985); Evans et al. (2012)	Data show induced seismic events of small magnitude associated with the fluid reinjection standard techniques. The natural seismicity occurring in the same areas makes the interpretation of some larger magnitude events trickier. These events are considered as being induced in some studies and natural in others.
Mt. Amiata	2000	3.9	Supposed	Mucciarelli et al. (2001, 2013)	
	1983	3.5	Supposed	Batini et al. (1990); Moia et al. (1993), Evans et al. (2012)	
Latera	1980	2.9	Documented	Batini et al. (1980b); Carabelli et al. (1984); Batini et al. (1990); Moia et al. (1993); Evans et al. (2012)	Data recorded during hydraulic stimulation experiments clearly highlight the occurrence of induced seismic events. These events are generally organized in sequences with magnitudes ranging from negative to the maximum specified value.
Torre Alfina	1977	3.0	Documented	Batini et al. (1980b); Moia et al. (1993); Evans et al. (2012)	
Cesano	1978	2.0	Documented	Batini et al. (1980b); Evans et al. (2012)	

Table 6 - Induced seismic events (documented and supposed) associated with geothermal activities in Italy (modified after Di Bucci et al., 2014)

Seismicity induced by geothermal production has also been hypothesized for the geothermal site of Casaglia, where geothermal fluids are used for the district heating of the town of Ferrara (central

Italy). The probability that the large seismic events recorded on 2012 in Emilia Romagna (M_w up to 6.1) had any connection to Casaglia's activities was considered "very low" by the International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Romagna Region (ICHESE), who were asked to debate the potential connection between the main earthquake and man-made activities such as hydrocarbon exploration (ICHESE, 2014).

3.6. Visual impact

The visual impact is a key factor in geothermal generation. Some of the buildings in Larderello are of historical and artistic interest and date back to the early 1800s. The new village of Larderello was designed by the worldwide famous architect Giovanni Michelucci and his unique style inspired the architecture of some machine buildings of power plants, e.g. Gabbro Power Plant built near Larderello. Larderello thus has a very unusual landscape, with historical buildings and natural draft cooling towers (Figures 5-7), providing the place with a visual identity that is recognised across the world. Nevertheless, visual impact mitigation has become increasingly important, and all the new plants are designed in harmony with natural landscape. Special care has been taken in some cases to develop trekking trails around the power plant to promote technological tourism.

Some pipelines have been camouflaged, but are considered as a unique feature of the area and do not raise concern.



Figure 5. San Martino power plant (photo by Fabio Sartori)



Figure 6. Bagnore 3 power plant, top view (photo by Fabio Sartori)



Figure 7. Nuova Monterotondo power plant natural draft cooling tower (photo by Fabio Sartori)

3.7. Waste

Geothermal power plants produce both liquid and solid waste, resulting from drilling wells and the construction, operation and maintenance of the plant, as well as urban waste from the personnel. During drilling, fluid and solid waste materials are produced, such as: i) drilling mud and other drilling fluid additives like cement slurry, diesel and lubricant, cleaning fluid waste and geothermal brine, and ii) cuttings, excavated earth and rocks, industrial waste of different types. Drilling muds are made up of a thixotropic mixture of water and clay (bentonite) and may also contain additives such as barium sulphate (barite) and synthetic polymers. Anionic polyelectrolytes (e.g., acrylates, polyphosphates, lignin sulphonates), are often used as fluxing agents during drilling to reduce the

viscosity of the drilling fluid. The brine extracted during drilling contains both salts and silica in variable amounts and composition, depending on the type of geothermal fluid.

Other waste resulting from the construction of a plant includes: excavated earth and rocks resulting from plant construction, unused materials from building access roads and pipe laying, plastics from packaging, metallic waste, waste timber, rubbery materials, filters and materials contaminated with lubricating oil and urban waste.

Packaging waste, lubricating oils, chemical agents (especially resulting from emissions abatement equipment or water treatment), parts of old machines (essentially consisting of ferrous and plastic scrap), urban waste, are also produced during the plant operation.

Table 7 shows the waste produced by drilling, reported from an environmental impact study of a pilot plant in Italy (Corsi et al., 2013). These quantities can vary depending on the characteristics of the well.

<i>Waste</i>	<i>Quantity (tons)</i>
Drilling muds (no reinjection)	310
Drilling muds (including reinjection well)	600 - 650
Packaging	0.5
Rubber materials	1.5
Waste timber	0.4
Waste oil	0.15
Filters and materials contaminated with lubricating oil	0.15

Table 7: Estimation of waste amount produced per drilling well (from Corsi et al., 2013)

Regulations

In the Italian law, waste is classified into urban or industrial waste. Waste from industrial activities is classified as “non-hazardous” (treated similarly to urban waste) or “hazardous”. Temporary storage of waste is allowed in an area within the production site, before disposal or recovery. Temporary storage does not require any authorization, but the waste must be disposed of or recovered at least quarterly, regardless of the volume, or whenever a volume of 20 m³ of non-hazardous waste, or 10 m³ of hazardous waste, is reached. In any case, waste cannot be stored for more than one year.

Hazardous and non-hazardous waste cannot be mixed. Waste disposal must be registered and a return form duly filled must accompany disposed waste during transportation. Excavated earth and rocks from drilling and construction can be reused or disposed.

Mitigation measures

The main measure adopted to minimize the waste amount from geothermal plants in Italy is full compliance with the regulations.

During drilling, solid waste is stored separately in special bins. Drilling fluids are collected and stored in sealed tanks, to be reused, and subsequently recycled (after debris separation and dehydration) or disposed of. To be reused and recycled, the drilling mud must be conveyed correctly, first in waterproofed sedimentation tanks, to separate the coarse debris, then in vibrating screens and/or filter presses. After removing the coarse portion, the mud is re-circulated into the drilling circuit. When the mud is no longer reusable, it is treated and disposed of: after the separation of the cuttings, the sludge is dehydrated in a filter press. Water is sent to a wastewater treatment plant, while the solid phase is usually sent to landfill sites. The brine extracted during the drilling is reinjected, or dehydrated (like mud) and sent to landfills.

Other waste (inert, wood, metal, cartons, plastic, etc.) is placed in appropriate containers and/or bins. Hazardous waste (such as oils and batteries) is stored in segregated and labelled containers. There is a specific storage area at the plants, and licensed waste management plants and carriers are appointed.

4. Social and economic aspects of geothermal energy in Italy

4.1. *Social and economic analyses*

The provision of safe and sustainable energy is one of the most complex, open and urgent issues of our times with technological, political, economic, social and even ethical challenges. The energy system is intricately woven into the social fabric and this means that no energy innovation can succeed without a comprehensive, social transformation: innovation is robust when it is socially sustainable (Stirling, 2013). The transition towards low carbon energy future is inevitably complicated and involves new forms of governance. The shift from government to governance i.e. “new styles of governing in which the boundaries between the public and private sectors, and the national and international levels have blurred” (Jordan et al., 2003, p. 8), entails including all relevant stakeholders in renewable energies development and in the management of new technologies. However, studies on forms of governance, social and economic aspects of geothermal energy have until recently been scarce in the international literature, at least compared to studies on other sources of renewable energy (see references in Pellizzone et al., 2015 and 2017)

A few studies on governance and socio-economic aspects of geothermal energy have been carried out in Italy. Here we describe the results and implications of three studies carried out in Italy in recent years. One was carried out in the context of advanced geothermal developments for energy production in Mt. Amiata, which has been hotly debated in the public arena (Borzoni et al., 2014). The other two case studies were conducted applying the same methodological scheme to the provinces of Palermo, Southern Italy, where no geothermal development has been planned, and

Viterbo, Central Italy, where geothermal development was proposed but has met some opposition (Pellizzone et al., 2015 and 2017).

Advanced geothermal developments: Mt. Amiata

A social multi-criteria evaluation of alternative scenarios for geothermal development was carried in Mt. Amiata (Borzoni et al., 2014). The aim was to explore the different legitimate perspectives of the actors involved, in order to incorporate evidence-based input into policy making, in an area where there has been considerable public unease surrounding competing scientific claims. The empirical analysis in the Mt. Amiata study considered seven different scenarios for the following 30 years, derived from four original assumptions: 1) the preservation of the status quo, 2) the projects planned by Enel Green Power at the time, 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, and 4) the formulation in “scenario terms” of the requests of the opponents to the Enel Green Power projects. All the scenarios were evaluated on a set of 11 criteria, grounded in a detailed analysis of institutional settings⁵.

The analysis systematically revealed how the evaluation of the criteria in the different scenarios correspond to the preferences and perspectives of the stakeholders, for example profit vs environmental concerns. The scenarios based on the status quo assumption resulted the least favourable. Scenarios involving binary cycles or total-reinjection technologies (related criticalities were not discussed and taken into account in this work) tended towards the most positive positions. While underlining that the aim of the study was to reveal the different perspectives of the stakeholders involved as input into socially sustainable decision making in this field, the authors concluded, correctly, that the controversy would continue. As underlined by the same authors, the views of local communities and the general public in the area were not adequately taken into account in the analysis.

Social engagement in Italy: Palermo and Viterbo

The two case studies described below were designed and conducted to define the social aspects related to the development of geothermal energy.

The case studies applied a mix of (1) quantitative (survey) and (2) qualitative (focus groups) research methods and were conducted in the Provinces of Palermo (Sicily, southern Italy), in autumn 2012 (Pellizzone et al., 2015) and Viterbo (Latium, central Italy), in spring 2014 (Pellizzone et al., 2017). The two areas were selected due to their high geothermal potential and their different geographical and social contexts.

The province of Palermo, was undergoing rapid deindustrialization, and geothermal resources had never been used for energy production there. On the other hand, Viterbo is geographically very close

⁵ The criteria were: 1) electricity produced, 2) profitability of the plants, 3) municipality revenues, 4) direct heat use, 5) avoided greenhouse gas (GHGs) emissions, 6) H₂S emissions, 7) Hg emissions, 8) NH₃ emissions, 9) As emissions, 10) possible impact on the phreatic aquifer, 11) visual impact.

to Mt. Amiata, and is in a region of Italy with unsuccessful past attempts to harness resources for energy production. Viterbo is located in an area where geothermal development with novel technologies has been proposed but has experienced a growing opposition including a committee of the local mayors that are against geothermal energy.

The survey (quantitative research) involved 400 people in each of the two provinces and the sample population was calibrated by a series of variables including age, gender, job position, education and place of living. There were four homogeneous focus groups (qualitative research) for each case study consisting of students, members of the general public, decision makers and ex-workers from an industrial plant that was going to be closed (in Palermo), local politicians and environmental activists (in Viterbo).

The studies highlighted that the local context is a key factor in shaping social acceptance toward geothermal developments. Knowledge and opinions about energy sources were unsurprisingly strongly differentiated depending on the technologies. When asked how geothermal energy would impact their life in the next 20 years ("positively", "negatively", "no effects" or "I don't know"), the rate of "I don't know" answers was quite high in both areas: 42% in Palermo and 44% in Viterbo. On the other hand, in Palermo the rate of "optimistic" thinking that geothermal energy would have a positive impact on their future (18%) was identical to the rate of "pessimistic" ones thinking that geothermal energy would have a negative impact (18%), whereas in Viterbo the rate of optimistic respondents (46%) exceeded the pessimistic (6%).

The studies reveal low but different levels of knowledge about geothermal resources: the rate of respondents that had "heard" about geothermal energy was 17% in Palermo and 42% in Viterbo. However, both the results of the surveys and the analysis of the focus group discussions indicate some level of openness to possible developments. In both studies all the focus group discussions moved spontaneously from more techno-scientific issues towards trust-related issues such as distrust in the political system, in commercial companies and in how decisions would be taken.

In both case studies participants requested more information on geothermal technologies, showing considerable trust towards researchers as information sources (Figure 9). These are important and highly sensitive matters for future developments in this sector that need to be adequately addressed by major stakeholders - the public must feel that they have all the information they need to make informed decisions.

There were some other differences between the two cases. In Palermo, where the once strong industrial base has been eroded in recent years, potential employment and innovation prospects from geothermal development prevailed over environmental concerns. On the other hand, in Viterbo the issue of water contamination and environmental impact was a key part of discussions. In Viterbo water is being contaminated by arsenic and drilling is seen as a threat to local rivers, lakes, underground waters and the ecosystem as a whole. The controversies over geothermal energy in Viterbo raised similar concerns as those in nearby Mt. Amiata, consequently future sustainable

governance of developments in this sector could benefit from lessons from Mt. Amiata. In summary, when planning developments in this sector it is of paramount importance to take into account the views and concerns of all the major stakeholders, including local communities and citizens. Social acceptance is highly contingent upon perceptions of responsible management of the utilization of natural resources and in today's citizens expect to have their voices heard.

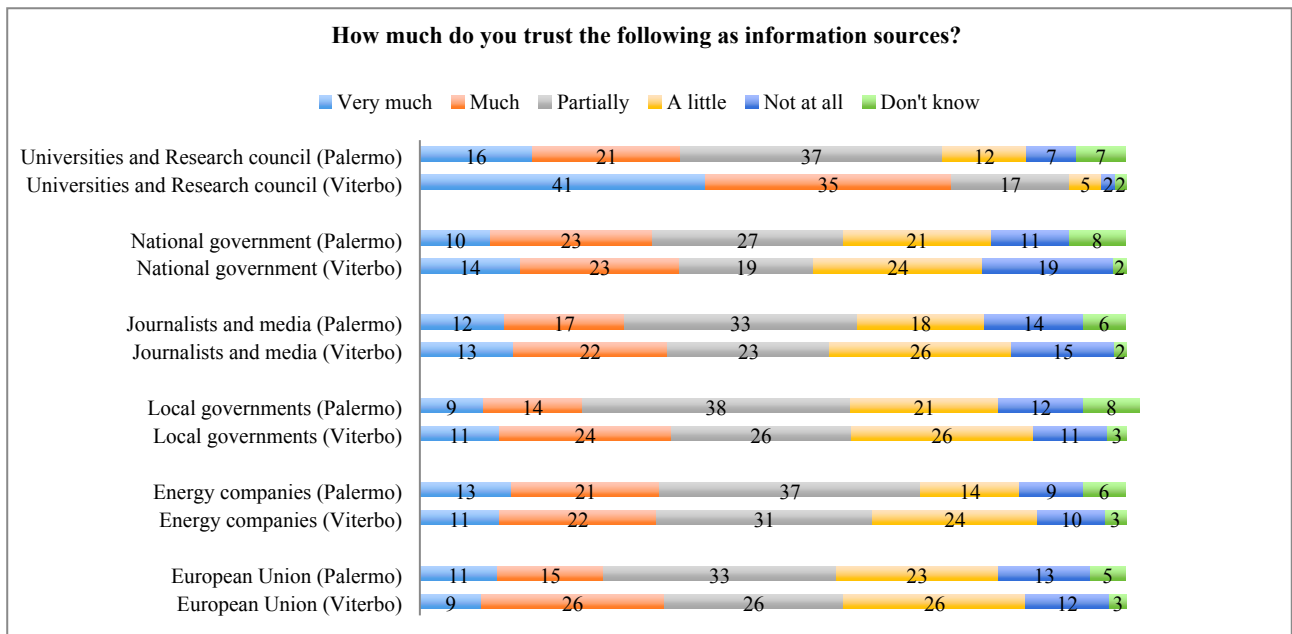


Figure 9 – Level of trust in a series of information sources

4.2. Local use of geothermal energy and social benefits

One of the main goals of Enel Green Power is to create long-term positive value for local communities in geothermal areas, thereby promoting both economic and social growth coming from geothermal development. Considering both direct and indirect employments, geothermal production impacts on more than 2000 workers living in local municipalities (about 750 employees directly involved in geothermal energy and more than 1300 indirectly) (Enel Green Power, pers. com.).

The 'indirect' employees work for local Enel Green Power contractors operating in various business sectors such as services, civil works, electro-mechanical, mechanical industry and carpentry. Further, thanks to the collaboration with Enel Green Power, these local companies often have the chance to expand, obtain knowhow and commercial success, and become international leaders in the geothermal business sector.

Enel Green Power also supports the wood industry that has recently been promoted by the development of biomass and cross-technology (geo+bio) power plants with a turnover of more than 1 M€/year and strong prospects for growth (Enel Green Power, pers. com.).

Another important geothermal sector is the “heat supply chain”: Enel Green Power promotes a sustainable life-style, providing about 330 TCal/year for heating processes derived from an intelligent use of geothermal fluids. In the past 30 years, Enel Green Power has built several district heating

systems to serve six local municipalities, with more than 10,000 users, and about 300,000 m² of greenhouses. Geothermal heat is also used for industrial processes, such as chemical processes or food industries, contributing to the growth of Slow Food producers, which is an important brand in Italy. Heat employment is estimated in about 300 people and avoided emissions are estimated to amount to more than 650 ktep/year (Enel Green Power, pers. com.).

Geothermal production areas have truly unique landscapes as well as geysers and trekking trails, which attract tourists from various parts of Italy and Europe. This tourism is also supported by a year-round program of cultural and leisure events such as “Open Power Plants” or “San Galgano Opera Festival” sponsored by Enel Green Power. In 2016 there was a record 60,000 tourists visiting geothermal places thus highlighting a promising future for the development of tourist facilities. Local social needs are also supported by fees paid by Enel Green Power to the municipalities of each concession area, for a total amount of more than 30 M€/year.

Enel Green Power also supports business-oriented initiatives taking advantage of local availability of geothermal fluids, such as the recent “Alga Spirulina” cultivation, or start-ups requiring specific skills (e.g. in the precision mechanics industry) through a close collaboration with professional schools, local universities and research institutions.

5. Conclusions

Through local administrations the Italian government is committed to ensuring that all geothermal activities are subject to rigorous environmental control. After collecting and organizing the data and information provided by the official records and scientific papers, this paper has analysed the environmental aspects of geothermal development in Italy related to air, noise, water, subsidence, seismicity, visual impact and waste, focusing on high temperature geothermal resources used above all for power production, whose environmental aspects of geothermal development have been extensively controlled and monitored in Italy for decades. The associated risks, all the reference data and adopted forms of mitigation and/or abatement measures have been discussed. Care for the environment and reducing the potential impact of geothermal energy to a safe level are fundamental to environmental policies in Italy. Considering the strategic role played by geothermal energy, local administrations and the government have enforced national legislation, providing guidelines for the correct exploration, operation and management of geothermal resources. In Tuscany, where all the geothermal power plants in operation are located, the regional government implements strict controls on environmental aspects, obtained by applying the most advanced mitigation techniques at the plants and periodic environmental monitoring and quality check.

Despite the fact that geothermal development in Italy is among the most controlled and environmentally friendly in the world, there are frequent disputes and opposition to the development of geothermal energy. After the first wave of criticism raised in the Mt. Amiata area, whose concerns

ranged from the visual impact to air emission to contamination and depletion of water in Tuscany, opposition groups now spring up when any new geothermal development is proposed, even when novel technologies are involved such as zero-emission plants.

The debate on geothermal energy is tied to the debate on other energy technologies (i.e. renewables, nuclear, shale gas). In Italy, the issue of deep drilling was reignited by the questions opened by the 2012 earthquake in northern Italy: had energy-related human activities in the area trigger these seismic events? The debate is also strongly linked to the issue of shale gas fracking related to oil and gas but not geothermal energy, which was triggered in the US but has become highly contentious in Europe too. In addition, seismic risks related to hard stimulation techniques, which have been used in Enhanced Geothermal System (EGS) projects in Europe but currently not used or scheduled in Italy, is often extended to any geothermal technology.

Partial or incorrectly provided information represents a serious threat to geothermal development. In the social arena, improved and accurate communication grounded in facts and data plays a strategic role. The fragmentation of information, uncertainty and doubts about the reliability of sources of data is a common problem, in Italy as elsewhere. We thus believe that the data in this paper would help combat this fragmentation of information. A regular and comprehensive review of the environmental and safety regimes of geothermal development would certainly benefit the geothermal sector.

Another key issue is: how can the geothermal sector engage more effectively with the society and include the social values in the innovation process? Rather than just focusing on alleviating public fears of potential risks, a key determinant of the acceptability of geothermal developments is to clearly explain the benefits, for example the reduction of utility bills and taxes, increased employment, and innovation development. The acceptability of the product (geothermal energy) is strongly influenced by the acceptability of the process (decision making, benefit distribution criteria...).

In Italy distrust in policy makers is a key limiting factor for geothermal development support: public engagement is supported, but at the same time people do not feel sufficiently informed to have a voice in decision making (Pellizzone et al., 2017). However, trust in scientists suggests that the empowerment of a dialogue between experts and non-experts should be strongly encouraged.

Social and environmental aspects represent two important pillars for the development of any form of energy harnessing, and Italy, with its impressive geothermal resources, high demand for energy and a vibrant society, is in the front line for facing the challenges offered by the harnessing of geothermal energy resources.

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efficiency, environmental protection, agro-food innovative methodologies for the Made in Italy, and biotech medicine production (see Giamberini et al., 2016 for detailed reference to Italian legislation). One of the social engagement case studies was performed within the framework of the VIGOR Project, aimed at assessing the geothermal potential and exploring geothermal resources of four regions in southern Italy. VIGOR was part of the activities of the Interregional Programme “Renewable Energies and Energy Savings FESR 2007-2013 – Axes I Activity line 1.4 “Experimental Actions in Geothermal Energy”. We thank the two anonymous reviewers and the Editor for their comments, resulting in an enriched and improved version of the paper.

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