Current status of the high enthalpy conventional geothermal fields in Europe and the potential perspectives for their exploitation in terms of EGS

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Abstract

The electrical energy production from geothermal power plants in Europe comes almost entirely from Iceland, Italy, Russia (Kamtchatka and Kuril islands), France (Guadeloupe, French West Indies), Portugal (Azores) and Turkey. Installed generating capacities are respectively 202, 790, 79, 15, 16 and 20.4 MWe. The temperatures are 190-340 ºC, 150-350ºC, 200-300 ºC, 250 ºC, 250 ºC and 140-240ºC, respectively. The percentage with respect to their National Energy is 16.6 % for Iceland, 1,9% for Italy, 9% for France (only referred to Guadeloupe Island), 25% for Portugal (only referred to San Miguel Island), while it is ranked negligible for Russia and Turkey.

Exploited reservoir depth ranges from shallow in Guadeloupe, Azores (0.3-1.1 km) to medium in Iceland (1-3 km), Russia and Turkey (1-2 km) to deep in Italy (1.5-4 km). In most cases the permeability is defined by fractures and faults, which are difficult to locate prior drilling.

Although some of these geothermal areas are among the most important in the world, they are probably not used at their maximum efficiency. EGS technology may enhance production from conventional high enthalpy fields, and is used only to a certain extent in some of these areas.

EGS methods that could be applied are various. Well stimulation methods to improve permeability of poor-producer wells; tracer tests and improved geophysical imaging to determine the extent of faulted reservoirs and prevent strong interference between wells; complete reservoir modelling; efficient scale inhibitors to prevent scaling in wells and surface pipes. All these are examples of goals that should be addressed in high enthalpy systems in the near future, in order to increase the contribution of geothermal power generation in Europe.

A review of the main characteristics of these geothermal areas will be given, as well as a discussion of their EGS potentiality.

France

The high enthalpy utilization for electricity production in France is in the French Overseas Department at Bouillante in Guadeloupe. The high temperature geothermal system is largely controlled by the volcanic and structural conditions of the island, and is located at the intersection between two fault systems.
The geothermal reservoir, with a brine composition of 60 % seawater and 40 % meteoric waters and a temperature of about 250-260°C, is intersected by wells between 300-1000 m depth.

The old Bouillante 1 double-flash power plant (4 MWe) is still operating after its rehabilitation in 1995-1996. A thermal stimulation was done in a poor permeable well (BO-4) in 1998 with benefits. Three new production wells were drilled in 2000-01 but only two are producers. A new 11 MW simple-flash power plant (Bouillante 2) has been in operation since 2004, raising the total capacity of the field to 15 MWe.

Production and tracer tests and geochemical results show that the reservoir is of large extension and connected to the sea. Geological reconnaissance and the existence of hydrothermal springs along the seashore and off shore in the Bay of Bouillante suggest that other geothermal resources possibly exist in the northern part of the bay.

An extension is currently in pre-feasibility phase. After the installation of the third unit, geothermal electricity should cover nearly 20% of the electricity consumed in Guadeloupe.

In the two other French Overseas Department (Martinique and La Réunion islands), geothermal exploration programmes for high enthalpy geothermal resources have been done. Next phase will be exploration drillings.

(Bertani, 2005; Fabriol et al., 2005; Laplaige et al., 2005)

Iceland

Iceland is a particularly favorable location for geothermal exploitation as repeated seismicity and volcanic activity in an environment of active rifting create high permeability and high temperature at shallow depths.
The geothermal resources in Iceland are closely associated with the country's volcanism. The high-temperature resources are located within the active volcanic zone running through the country from southwest to northeast. The oldest geothermal power plant in Iceland is in Bjarnarflag in NE-Iceland (Namafjall field) where a 3 MWe back pressure unit started operation in 1969. Since then, three high temperature geothermal fields have been exploited for power production, Krafla (60 MWe), Nesjavellir (120 MWe), and Svartsengi (46 MWe). Two new plants will start production in 2006 and 2007, Reykjanes (100MWe) and Hellisheiði (120 MWe). Both the Hellisheiði and the Nesjavellir power plants are within the Hengill volcanic system. Heat sources are represented by dike swarms or intrusions (e.g., Reykjanes, Hengill) or magma chambers (e.g., (Krafla). The geothermal fluids also show a strong variability, being seawater in Reykjanes and Svartsengi, meteoric water in Nesjavellir, and meteoric water enriched by volcanic gases in Krafla.

The systems are water-dominated hydrothermal fields, with temperature often above 300°C at 2.5 km depth. Pressure drop is either compensated by the rapid natural fluid circulation through porous and permeable reservoir rocks, or by reinjection.

Geothermal electricity production in Iceland is now rapidly increasing with time. It is expected to raise from 202 MWe in 2004 to 450 MWe in 2007. In addition exploration drilling is ongoing in 7 new production fields. Three of them are in N-Iceland, Krafla–West, Bjarnarflag and Þeistareykir, one in Central Iceland (Hágöngur) and three in SW-Iceland, two in the Hengill volcanic complex and one in the Trölladyngja. Intensive geothermal exploration surveys are on-going in 7 more high temperature fields in Iceland.

All the above mentioned power plants are conventional high temperature geothermal systems exploiting the energy down to 2-3 km depth. In addition there are plans to develop Unconventional Geothermal Systems. The main idea is to drill deep enough into the intrusion complexes of the volcanic systems to get supercritical fluids and exploit the enormous energy stored in the depth interval 3-5 km within the volcanic systems. The Iceland Deep Drilling Project is a part of these plans (see www.iddp.is).

(Bertani, 2005; Ragnarsson, 2005)

Italy

There are two major geothermal areas in Italy: Larderello-Travale/Radicondoli and Mount Amiata, both located in southern Tuscany. Due to environmental and technical problems, the 40 MW geothermal unit installed at Latera, northern Latium, has been decommissioned and this field is not currently under exploitation.
After the first experiment of geothermal exploitation carried out at Larderello in 1904, the first industrial power plant (250 kW) was put into operation in 1913, and geothermal power production has since increased continuously up to the present value of 790 MW installed capacity (699 MW running capacity).

Two geothermal reservoirs are exploited both in Larderello-Travale/Radicondoli and Mt. Amiata areas: a shallow reservoir within cataclastic levels of the carbonate evaporitic rocks of the Tuscan Complex, producing superheated steam, and a deeper, more extensive reservoir defined by fractures within the metamorphic rocks, at depths of more than 2 km. The deep reservoir is steam dominated in Larderello-Travale/Radicondoli whereas is water dominated in Amiata area with values of 20 Mpa and 300-350°C at 3 km.

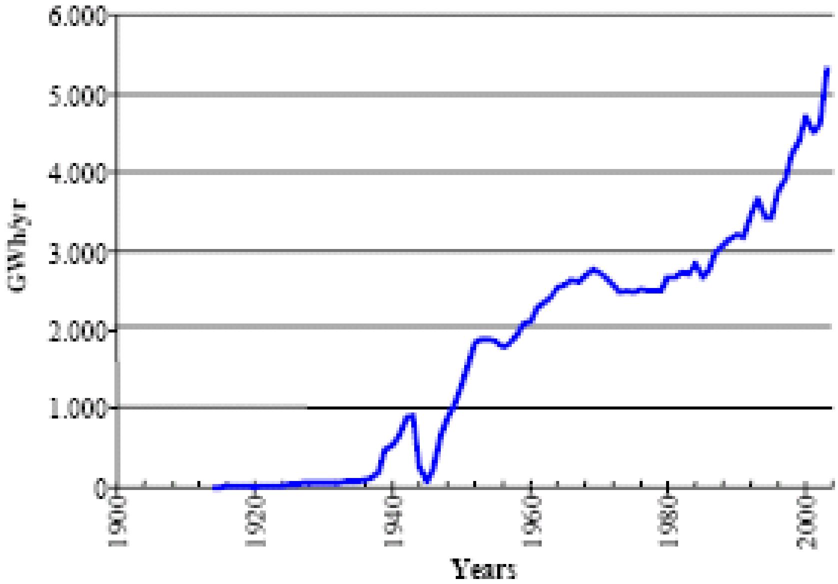
Larderello and Travale/Radicondoli are two adjacent parts of the same deep field, covering a huge areal extension of approximately 400 km^2: this deep reservoir has the same temperature (300-350°C) and pressure (4 - 7 MPa) everywhere. The field produces superheated steam at a rate of 850 kg/s in Larderello and 300 kg/s in Travale/Radicondoli. The exploited area of Larderello covers about 250 km^2, with 180 wells and 21 units giving 542 MW installed capacity; on the southeast the Travale/Radicondoli area covers about 50 km^2, with 22 wells feeding six units of 160 MW installed capacity. The condensed water from Travale is reinjected into the core of the Larderello field through a 20 km-long water pipeline.
Mount Amiata area includes two water dominated geothermal fields: Piancastagnaio and Bagnore. Presently there are 5 units with 88 MW of installed capacity: one in Bagnore and four in Piancastagnaio.

Since the late '70s, reinjection and deep exploration programs were begun in Tuscany with the aim of sustaining or increasing steam production. The reinjection of the steam condensate back into the reservoir has been very successful, especially in the most depleted area and made it possible to increase the reservoir pressure and, as a consequence, the steam production.

A total of 21 wells have been drilled in the last five years for a total of 64 km. The main effort since 2002 has been the replacement of old power plants for a better efficiency and a lower environmental impact. For this reason the installed capacity didn't increase in the last years, notwithstanding the relevant building commitment.
A further installation of 100 MW is expected in the next five years.
Serious acceptability problems with local communities are slowing down the project for the full exploitation of the high potential deep reservoir in Mt. Amiata area.

The electricity generation picked up to 5,430 GWh in the year 2003, that represent about 1.9% of geothermal electricity generation in Italy, as well as 25% of the electricity needs in Tuscany, the region where all the geothermal fields in operation are located.

(Bertani, 2005; Cappetti and Ceppatelli, 2005)



Two different increase phases are shown: the first in the period from ‘30s to mid ‘70s, related to the development of the shallow carbonate reservoirs; the second from the beginning of ‘80s up to now, when the fluid production has been increasing because of the positive results of the deep drilling activity and the artificial recharge of the shallow depleted reservoirs with the reinjection of the condensed steam and water.

Portugal

In Portugal, exploitation of geothermal resources for electric power generation has been developed successfully on the largest and most crowded of the Azores islands, São Miguel. The Azores archipelago, consisting of 9 inhabited islands of volcanic origin, is located in a complex geotectonic setting associated with the triple junction point of the North American, Euro-Asian and African plates.

In São Miguel island geothermal fluids in excess of 250ºC originate at depth near the summit area of the Fogo volcano and, above an elevation of -1,000 m, the fluid moves laterally to northwest in an extensive zone at least several hundred meters thick, in which temperatures exceed 220ºC. Pico Vermelho and Ribeira Grande geothermal power plants, with a total installed capacity of 3+13 MWe, supply over 25% of the electrical consumption of the island. A new geothermal power plant (10 MWe) is previewed to start production by the beginning of 2006, replacing the existing Pico Vermelho generation unit. A total of 5 to 6 production/injection wells are to be drilled in the scope of this project and as make-up wells to supply additional geothermal fluid to Ribeira Grande power plant.
In the island of Terceira, after the promising results of the exploratory drilling of geothermal gradient holes that showed a maximum temperature of 234ºC, a project for installing 12 MW is ongoing, expecting to supply approximately 50% of the consumption needs of Terceira Island by the year 2008.

(Bertani, 2005; Carvalho et al., 2005).

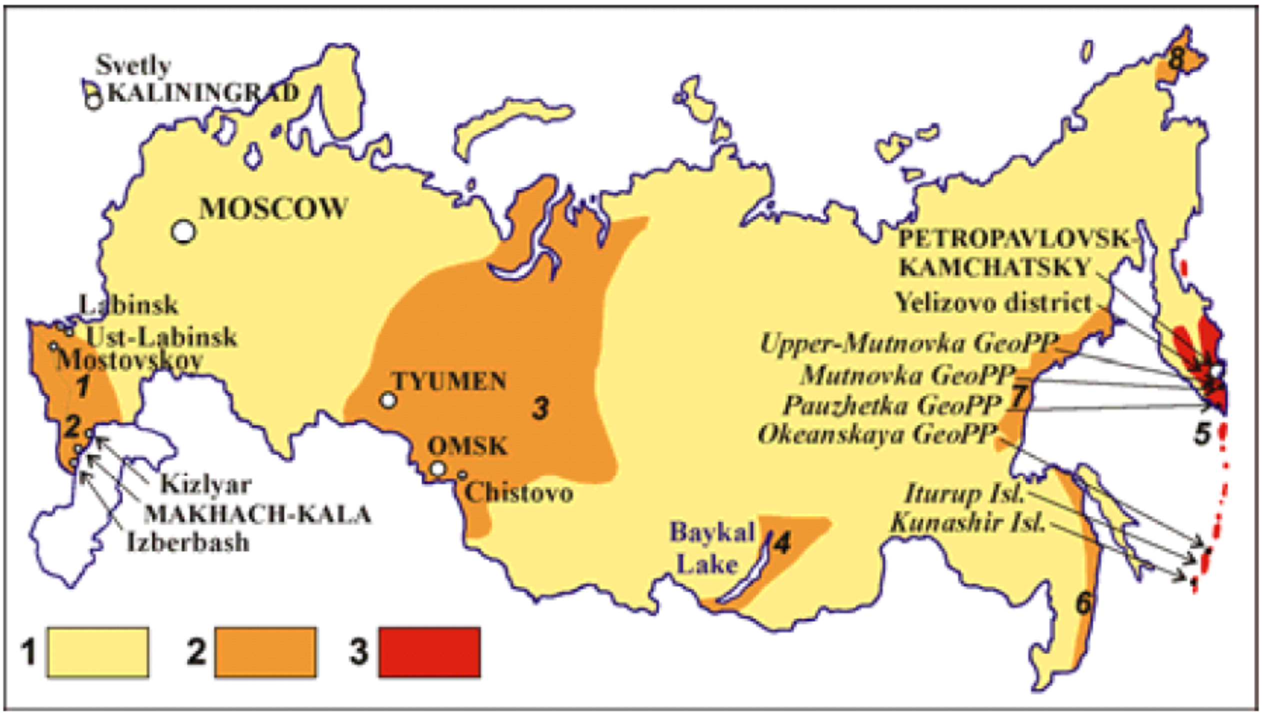
Russia

High enthalpy areas exploited for geothermal purposes are the areas of active volcanism in Kamchatka and Kuril Islands, in the far East Russia. The total installed capacity is 79 MW.

In Kamchatka three geothermal power plants are in successful operation: 12 MW and 50 MW on Verkhne-Mutnovsky and Mutnovsky fields respectively and 11 MW on Pauzhetsky field. The Projects of construction of binary Verkhne-Mutnovsky (6.5 MW) and the second stage of Mutnovsky GeoPP with the installed capacity of 100 MW are presently under development.
The vapor-dominated North Mutnovsky geothermal field has long been considered as the primary object for electric power production in Kamchatka. In total, 82 bore holes 255 to 2266 m in depth were drilled here, and a reservoir containing fluid (steam) with enthalpy 2100-2700 kJ/kg was found at depths of 700-900 m. It is underlain by a liquid dominated reservoir holding fluids with enthalpy 1000-1500 kJ/kg (T=250-310 0C). Now, 17 wells producing 330 kg/s of fluids with enthalpy 1600 kJ/kg in average are ready for exploitation. Three 4 MWe units are now in operation on the upper sector of the field called Verkhne-Mutnovsky sector. Two other units, single flash (3 MW) and binary cycle with organic actuating fluid (6.5 MW), are under construction in this sector now.
Except for the geothermal resources of the Kronotsky protected area, such resources revealed in Kamchatka to date could provide the electric power generation of 1130 MWe.

On Kuril Islands the Iturup Island power plant (3,4 MWe) is projected in future for generating 17 MWe. Here 9 wells are ready for exploitation. Another power plant (2.6 MWe) was constructed on Kunashir Island, the most southern Island of the archipelago

(Bertani, 2005; Kononov and Povarov, 2005)



1 - 3 – regions differentiated by hydrothermal resources utilization:

1 – suitable for heat supply to buildings with application of heat pumps; 2 – promising for "direct" utilization; 3 – regions of active volcanism being most promising for "direct" utilization, heat and power generation at binary plants / high capacity GeoPP (operating on steam-water cycle) on steam and hydrothermal fields.

Turkey

Kizildere Geothermal Field is the first and the only field of Turkey utilized for electricity generation.
The field was discovered in 1968, and electricity generation was started in 1984 with an installed capacity of 20.4 MWe. Since then, the power plant is producing with an average of 12-15 MWe.
The water-dominated geothermal system is made of two reservoirs, hydraulically connected. The shallow reservoir, located in limestone and/or marble at a depth of 600-800, has a temperature of 195-205°C. The limestone is not distributed homogeneously and is not encountered in all the wells. The marbles are much more continuous and thicker, and show a higher permeability, and therefore they were the primary targets for early exploration. The deep reservoir, at about 1400-1500 m depth, has a temperature of maximum 240°C and is located in gneiss. The geothermal fluids contain 1,5 % non-condensable gases. The amount of these gases at the separation pressure in the single flash plant is 15 % in weight. A liquid CO^2 and dry ice production factory is integrated to this power plant which produces 120,000 tonnes of liquid carbon dioxide and dry ice annually.
The fluid produced flows to separators; while the separated steam goes to turbine to generate electricity, the water with a temperature of 147 °C is directed to silencers and then discharged. Since 1984, the separated water having a boron concentration of 25-30 ppm has been discharged to the nearby river, creating environmental hazard.

Reinjection operations were started in 1995 to tackle operational problems such as Boron discharge to the nearby river and decline in reservoir pressure.
The results indicate a marginal cooling effect in the well closest to the reinjection well. The allowable production rate from the field increased from 830 tons/h up to 1000 tons/h without experiencing a decline in reservoir pressure. The well R-2 is capable to re-inject economically about 20-25 % of waste water provided from the separators of production wells by gravity.

(Bertani, 2005; Simsek et al., 2005; Yeltekini and Parlaktuna, 2006)

EGS techniques and how they could improve high enthalpy geothermal fields

The work programme of the priority thematic area 1.6, "Sustainable energy systems", defines a need for co-ordinating ongoing research and promoting the development and uptake of innovative methods and technologies to expand the exploitation of Unconventional Geothermal Resources, in particular Enhanced Geothermal Systems.

Different ways have been tested or are imagined for enhancing and broadening geothermal energy reserves which can be classified into Unconventional Geothermal Resources, i.e. mainly Enhanced Geothermal Systems (EGS) and Supercritical Reservoirs:

- stimulating reservoirs in Hot Dry Rock systems,
- enlarging the extent of productive geothermal fields by enhancing/stimulating permeability in the vicinity of naturally permeable rocks
- enhancing the viability of current and potential hydrothermal areas by stimulation technology and improving thermodynamic cycles,
- defining new targets and new tools for reaching supercritical fluid systems, especially high-temperature downhole tools and instruments,
- improving drilling and reservoir assessment technology,
- improving exploration methods for deep geothermal resources.

The application of stimulation techniques to high enthalpy systems results in broadening the reservoirs. This would correspond to a potential increase of exploitation and hence of power production, and at the same time the sustainability of resources would be guaranteed for a very long period. High enthalpy fields are the obvious base for the exploitation of supercritical fluids, which can be found in these fields at drillable depths. High enthalpy steam produced by these fluids would generate a much higher electric power than conventional geothermal wells.
However, the importance of high enthalpy fields is not only restricted to themselves, but to the entire geothermal scenario. These fields should be considered as ideal laboratories for experimenting new ideas for geothermal exploitation, since the more accessible depth of interesting temperatures would decrease the cost of the experiment, being the drilling usually the most expensive part of geothermal exploitation.
Moreover, long-exploited fields such as in Italy and Iceland, where a huge amount of data is already available, may serve as demonstration plants for a variety of tests in order to improve the reservoir assessment technology and the exploration methods.

Well stimulation methods to improve permeability of poor-producer wells are the most common among the technologies derived from EGS and applied to conventional fields. They were successfully applied in Italy, Guadeloupe and could be profitably applied in other fields, wherever the permeability appears reduced.
Tracer tests are now becoming a tool for detection of reservoir volume and prevent strong interference between wells, in particular during reinjection. They have been applied in Turkey, Iceland?? and may provide useful information in all the exploited fields.
Efficient scale inhibitors to prevent scaling in wells and surface pipes are becoming very important for the maintenance of exploitation.

Improved geophysical imaging tools to determine the extent of faulted reservoirs as well as integrated reservoir modelling have been developed during the EGS experiments. Their application to conventional system may provide a new insight in geothermal structures that are, by definition, very complex. Time lapse geophysical measurements have proved to be particularly effective in exploring the dynamic of EGS, but their application is not common in conventional fields. The improvement of technology and reduction of costs are making them particularly attractive in any kind of geothermal system. The combination of different data through integrated modelling are helping in defining both static and dynamic geothermal features and should be applied in all fields to reduce the mining risks and improve the control of the system.

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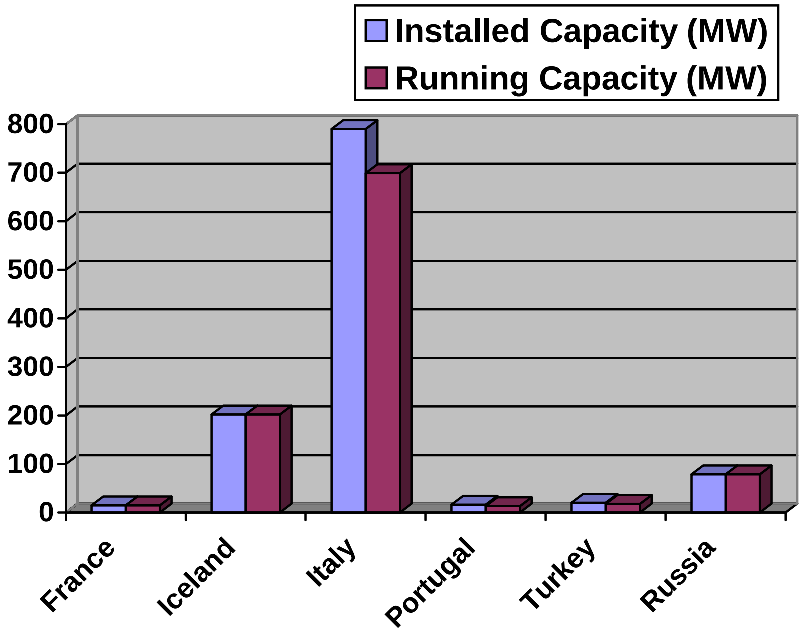
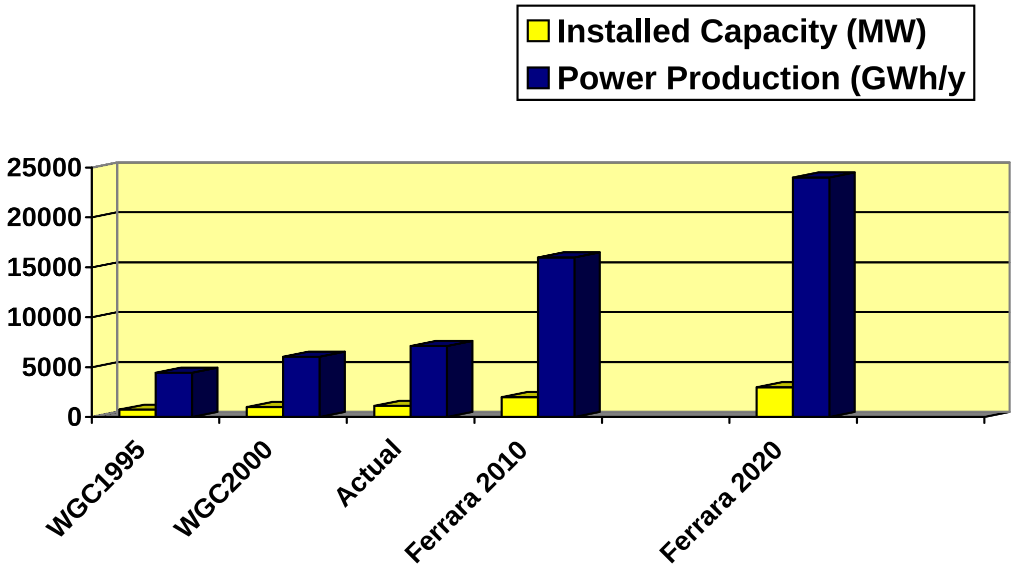
Country	Field	Drilled area (km^2)	Geology	Type	Depth (m)	Temperature ºC	Wells (production)	Wells (reinjection)	Running capacity
France	Guadeloupe	1	Volcanic	Water	300 1100	250	3		15
Iceland	Krafla	5-6	Volcanic	Water	1000 2000	190-210 350	21	1	60
	Nesjavellir	6-8	Volcanic	Water	1000 2000	300-320	18		90
	Svartsengi	6-8	Volcanic	Water	1000 2000	240	11	1	46
	Reykjanes	4	Volcanic	Seawater	3000	290-320	14	0	(100)
	Hellisheiði	6-8	Volcanic	Water	3000	240-280	18	5	(120)
Italy	Larderello	250	Metamorphic	Steam	1000 4000	150-270 350	180	23	473
	Travale Radicondoli	50	Metamorphic	Steam	1000 4000	190-250 350	22		147
	Bagnore	5	Metamorphic	Water	1000 3000	200-330	7	4	19
	Piancastagnaio	25	Metamorphic	Water	1000 3000	200-300	19	11	60
Portugal			Volcanic	Water	>700	100-150	5		13
Russia	Pahuzhetka		Volcanic	Water		200	7		11
	Mutnovsky	12-15	Volcanic	Water/ Steam	700 2500	240-300	17	4	62
Turkey	Kizildere		Metamorphic	Water		240			17

Country	Wells drilled in 2000-2005	Installed capacity [MW]	Running capacity [MW]	Annual Energy produced [GWh/y]	Number of Units	% of National Capacity	% of National Energy	2005-2000 Increase installed capacity [MW]
France	3	15	15	102	2	9% Guadeloupe island	9% Guadeloupe island	11
Iceland	23	202	202	1406	19	13.7%	16.6%	32
Italy	21	790	699	5340	32	1.0%	1.9%	5
Portugal	2	16	13	90	5	25% San Miguel island		
Turkey	4	20	18	105	1	Negligible	Negligible	0
Russia	4	79	79	85	11	Negligible	Negligible	56


Installed Capacity (MW)
Running Capacity (MW)
800
700
600
500
400
300
200
100
0
France
Iceland
Italy
Portugal
Turkey
Russia


Installed Capacity (MW)
Power Production (GWh/y
25000
20000
15000
10000
5000
0
WGC1995
WGC2000
Actual
Ferrara 2010
Ferrara 2020