Strategic Research Priorities for Geothermal Electricity

Technology Platform on Geothermal Electricity (TP-Geoelec)
Strategic Research Priorities for Geothermal Electricity

Technology Platform on Geothermal Electricity (TP-Geoelec)
AUTHORS

The members of the TP Geoelec

In particular (in alphabetical order):
Marco Baresi – Turboden, IT
Ruggero Bertani – ENEL Green Power, IT
Christian Boissavy – AFPG, FR
Paola Bombarda – Politecnico di Milano, IT
Christoph Clauser – RWTH Aachen, E.ON Research Center, DE
Jean-Philippe Gibaud – Schlumberger, FR
Florence Jaudin – BRGM, FR
Constantine Karytsas – CRES, EL
Thomas Koelbel – EnBW, DE
Attila Kujbus – Geothermal Express Ltd., HU
Horst Kreuter – GT Eng. GmbH, DE
Céline Mahieux – ABB, CH
Adele Manzella – CNR-IGG, IT
Dimitrios Mendrinos – CRES, EL
Carlo Minini – Turboden, IT
Burkhard Sanner – European Geothermal Energy Council, EU
Pierre Ungemach – GPC IP, FR

EDITOR:
Secretariat of TP Geoelec
Philippe Dumas – European Geothermal Energy Council, EU

Renewable Energy House
63-67 Rue d’Arlon
B-1040 Brussels - Belgium
www.egec.org
com@egec.org

Manuscript completed in April 2012.
Brussels, © EGECE 2012.
This document is available on the Internet at: www.egec.org

DISCLAIMER

The opinions expressed in this document are the sole responsibility of the Technology Platform on Geothermal Electricity and do not necessarily represent the official position of the European Commission. Reproduction and translation for non-commercial purposes are authorised, provided the source is acknowledged and the Editor is given prior notice and sent a copy.
Table of Contents

1. A EUROPEAN VISION FOR GEOTHERMAL ELECTRICITY......................................................................................................................4
   1.1 INTRODUCTION ...........................................................................................................................................................................5
   1.2 TODAY .........................................................................................................................................................................................................................6
       1.2.1 WHAT IS GEOTHERMAL ELECTRICITY PRODUCTION? ........................................................................6
       1.2.2 EUROPEAN GEOTHERMAL INDUSTRY STAKEHOLDERS................................................................................9
   1.3 TO 2020: LAYING THE FOUNDATIONS OF A EUROPEAN GEOTHERMAL INDUSTRY ..........10
   1.4 TO 2030: MAKING EGS A COMPETITIVE SOURCE OF ELECTRICITY .................................................................11
   1.5 BEYOND 2030: POWERING EUROPE AND THE WORLD FROM GEOTHERMAL ..........12

2. STRATEGIC RESEARCH AGENDA FOR GEOTHERMAL POWER GENERATION TECHNOLOGY ..............13
   2.1 INTRODUCTION .............................................................................................................................................................................14
   2.2 TECHNOLOGY STATE OF THE ART ...........................................................................................................................................15
   2.3 TECHNOLOGY DEVELOPMENT OBJECTIVES .........................................................................................................................23
   2.4 RESEARCH PRIORITIES .................................................................................................................................................................27
   2.5 ROADMAP FOR 2020/2030 BEYOND ........................................................................................................................................29

3. REFERENCE: GEOTHERMAL ELECTRICITY .................................................................................................................................30
1. A European vision for geothermal electricity
1. A EUROPEAN VISION FOR GEOFHERMAL ELECTRICITY

1.1 Introduction

This document presents the vision of the European geothermal electricity industry. It completes the Vision and the Strategic Research Priorities for Geothermal Heating & Cooling.

Starting with the present situation, the Vision sets out in global terms how geothermal stakeholders see the future development of their industry. It reflects the basic features of geothermal electricity production, the way the systems are expected to evolve and how the industry and associated stakeholders should evolve to make it happen.

Challenged by climate changes and the need to secure sustainable economic growth and social cohesion, Europe must achieve a genuine energy revolution to reverse today unsustainable trends and live up to the ambitious policy expectations. A rational, consistent and far sighted approach to electricity supply is critical for ensuring such transformation.

Geothermal is the only source of renewable energy capable of driving such a consistent and reliable electricity generation 24 h per day, 365 days per year. Geothermal energy utilization is based on harvesting the heat content and continuous heat flux coming from the earth, which represents 25 billion times the world annual energy consumption, therefore representing an almost unlimited and renewable source of energy. This heat flux from the earth to the atmosphere, if not harvested, is otherwise lost.

As geothermal energy is available everywhere, local geothermal electricity production will reduce the reliance on imports from unsecure suppliers, averting conflict between nations. The lack of a secure and affordable source of energy is always highlighted as one of the reasons for under-development; by removing dependence on fossil fuel imports geothermal energy alleviates a big burden on developing countries’ budget. In addition, the integrated use of heat and power has shown to have an even bigger effect on job creation due to the resulting spin-off companies using the geothermal heat (green houses, fisheries, food processing, refrigeration, etc).

This document aims to draw a realistic picture of how a European Geothermal Electricity production industry can be built, which will effectively lead towards developing a reliable and sustainable source of energy and providing numerous jobs for all kinds of qualifications across the area. The roadmap to large scale geothermal power development is as follows.

By 2020: Establishing the base of a European geothermal industry

- Develop the hydrothermal resources in Europe from the known High enthalpy resources (Italy, Aegean volcanic arc and ultra-peripheral regions), and from Medium enthalpy resources (Continental basins, islands and regions with neogene volcanism, etc.), and also in non-EU countries (Turkey and the Caspian area, African rift, South America, etc.). This last aim is attractive for Europe’s balance of payments where exporting is important.

- Expand the EGS concept in the different regions and geological conditions of Europe through the construction of power plants and direct uses of heat, thus maintaining the leadership in this new field.

1 The total heat content of the Earth stands in the order of 1.26 x 10^24 MJ, and that of the crust of 5.4 x 10^21 MJ, indeed a huge figure when compared to the total world energy demand which amounts to ca 5.0 x 10^14 MJ/yr i.e. the earth contains enough heat to cover the needs of humanity for 25 billion years with present energy consumption rate, not counting its replenishment by radioactive decay of natural isotopes, which has been estimated as 30 x 10^13 GW or approximately 2 times present worldwide energy consumption. A very detailed estimation of the heat stored inside the first 3 km under the continents dates back to 1978, applying an average geothermal temperature gradient of 25 °C/km depth for normal geological conditions and accounted separately for diffuse geothermal anomalies and high enthalpy regions located nearby plate boundaries or recent volcanism. The high enthalpy regions cover about ten percent of the Earth’s surface. The total amount of available heat is huge, about 42 10^18 MJ. With the present world energy consumption the geothermal heat can be fulfill the world need for about 100,000 years.
technology development. This also includes the development of a more efficient binary cycle for low temperature resources.

• Establish the basis for a European model of geothermal power plants in harmony with the environment: e.g. medium size plants with fluid re-injection to minimize the impact on landscape, environment and the Grid, and to maximize the benefit to communities through an innovative use of rejected hot fluid from the power plant.

• Launch EU wide exploration programs to allow optimum funding allocation between the different underground potential uses (including geothermal, gas storage, O&G exploration and production, mining nuclear waste repository and carbon storage)

• Europe has pioneered in the exploitation of geothermal resources for power generation for over 100 years in Larderello and the EU still maintains a leading role due to the development of EGS technology in many parts of the EU with the integration of national projects (in UK and Germany) into a European Project at Soultz-Sous-Forêts (France). In addition, the EU has the first successful commercially funded EGS project in Landau (Germany). Considering that the rest of the world is moving towards geothermal energy with an accelerated pace, these efforts need to be maintained and further expanded ambitiously in order to keep this leadership in developing the geothermal industry of the future, both for research and commercial development.

By 2030: towards a competitive source of electricity

• Bring down the cost of EGS plants by technical developments, in order to become competitive with other sources of energy.

• Start implementation of massive construction programs for geothermal power plants in order to replace ageing and increasingly costly fossil fuel based power plants, starting with the most promising areas.

• Transfer EGS technology outside Europe in areas lacking hydrothermal resources thanks to the technical expertise developed and the capability of the European industry to develop large engineering projects around the world.

• Develop mature technologies for exploitation of supercritical fluids and temperatures, and start exploitation of large off-shore geothermal reservoirs and ultra deep geothermal resources.

Beyond 2030: a substantial part of the base-load electricity supply

• By that time technology will allow EGS to be developed everywhere at a competitive cost, the challenge will then be to implement it widely and quickly enough to capture a large market share from other type of base-load power plants (Coal, nuclear, fuel, etc) in Europe and outside Europe with a target for 2050 of 320 GWe or ~20% of total installed power capacity.

1.2 Today

1.2.1 What is geothermal electricity production?

The systems for geothermal electricity production can be subdivided in three main categories, which are also linked to the temperature ranges:

• 80°C<T<180°C (Medium Enthalpy resources): this range of temperature is appropriate for use with binary plants (Organic Rankine or Kalina cycle), with typical power in the range 0.1-10 MWe. These systems are also suitable for heat & power co-generation, typically for single edifice to small towns heating.

• 180°C-390°C (High Enthalpy resources): temperatures in this range can be exploited with dry steam,
flash and hybrid plants, with typical power in the range 10-100 MWe. These systems, characterised by high efficiency up to more than 40%, also allow heat co-generation for large towns’ district heating. Above 200°C, these resources are generally limited to volcanic areas.

- 390°C-600°C (Supercritical unconventional resources): temperatures in this range, limited to volcanic areas, generally involve superheated dry steam plants, with power per unit volume of fluid up to one order of magnitude larger than conventional resources.

Besides the temperature range, the methods of exploitation of geothermal energy can be further subdivided in two main categories:

- conventional hydrological systems, which use natural aquifers
- EGS (Enhanced Geothermal Systems), which use the high temperature of rocks with artificial water injection and, generally, with enhancement of permeability of the hot reservoir. An Enhanced Geothermal System is an underground reservoir that has been created or improved artificially.

A total of ca 530 geothermal units all over the world were reported online in 2010. The maximum addresses 236 binary plants, totalling a 1178 MWe installed capacity (i.e. a unit 5 MWe plant load). The sizes of flash and dry steam plants average 31 MWe and 44 MWe respectively.

In the EU, the total installed capacity is ca. 850 MWe (approximately 0.1% of total installed power capacity), generating about 7 TWh in 2010. Main production comes from conventional geothermal systems in Italy. Recently, binary power has been produced in Austria and Germany from low temperature geothermal sources and in France and Germany from EGS.

At present, projects representing a total of 400 MWe are ongoing in the EU (EGS and low temperature power plants).

**Hydrothermal**

As far as conventional geothermal electricity is concerned, the vast majority of eligible resources for large scale geothermal development in Europe are concentrated in Italy, Iceland, Greece and Turkey.

There are two major geothermal areas in Italy, Larderello-Travale/Radicondoli and Monte Amiata respectively, achieving 843 MWe of installed capacity in 2010. Projects, adding a further 100 MWe capacity, have been commissioned and will be completed in the near future.

Iceland is increasing its electricity production, which reached a 575 MWe installed capacity in 2010. Although significant, this capacity ought to be compared to the huge potential of the island, estimated at ca 4000 MWe. The country has recently started pioneering researches about the exploitation of supercritical fluids, able to increase of one order of magnitude the power output of geothermal wells.

Turkey’s geothermal resources are mainly located in Western Anatolia on the Aegean Sea façade. New geothermal power plants have been recently installed. The national geothermal electricity potential has been (conservatively) estimated at 200-300 MWe.

In Greece, proven shallow high temperature geothermal resources are located in the Aegean volcanic island arc, in the Milos (Cyclades) and Nisyros (Dodecanese) islands. Recent volcanism and abundance of hot springs indicate the presence of high enthalpy resources at 2-4 km depth in many other places. Preliminary estimation of geothermal potential from hydrothermal resources gives a figure of the order of 1500 MWe.

A similar situation exists in the small fields of the Guadeloupe and Azores volcanic islands. At Bouillante (Guadeloupe, France), a small, 4.7 MWe rated, plant was built in 1984. Its capacity has recently been increased to 15 MWe.
In the Sao Miguel Island (Azores, Portugal), 43% of the electrical production is supplied from high temperature (230°C @ 1200 m) saline brine, by three flashed steam plants (23 MWe total installed capacity) online since 1980. An additional 12 MWe capacity is scheduled in the near future.

In Spain, good perspectives can arise from the exploration on the volcanic systems of the Canaries islands, where a potential of about 50 MWe can be assumed to lay.

• Binary plants

Recently, binary power is produced in Austria, Turkey and Germany from low temperature geothermal sources. The conversion process which consists of vaporising a low boiling point working fluid, either a hydrocarbon or refrigerant -Organic Rankine Cycle (ORC) - or an ammonia/water mixture- Kalina cycle- raises considerable interest as it makes it possible to produce electricity from cooler geothermal sources (typically within the 100-120°C temperature range, exceptionally down to 70-75°C depending upon the availability of a cold water source for re-condensation of working fluid). However, no high plant ratings can be expected for obvious thermodynamic reasons. Hence, improvements should concentrate on cycle and plant efficiencies alongside cogeneration of heat. As a result, two development routes are contemplated

• plant designs targeted at 5 – 8 MWe CHP or power only capacities presently under development in EU, higher than the medium binary plants installed capacities

• small plant designs targeted at 1MWe/2MWth CHP capacities, close actually to those implemented already in the EU [(0.5 - 3 MWe) / (1-6Mth)], and

• a microgeneration standard for small scale ORC modules (200 kWe – 1 MWe)

• EGS

To the question of how could geothermal energy expand its power market penetration share, the EGS issue is the answer. The rationale behind the concept is the following: whereas drilling technology is in the mature stage and efforts dedicated clearly to reducing its costs, especially for ultra deep wells, stimulation technologies of geothermal rock environments are still in the pilot stage. There exist many geothermal prospects enjoying high temperatures but lacking sufficient rock permeability to allow fluid circulation. Such tight rock, poorly conductive, systems could be turned into technically and commercially exploitable reservoirs, provided their permeability is enhanced by engineering adequate stimulation procedures, such as hydraulic fracturing and acidising. Development of these technologies will make it possible to access a huge geothermal potential.

An EGS plant today has a capacity of 3-10 MWe, but future commercial plants will have a capacity of 25-50 MWe (producing from a cluster of 5 to 10 wells like in oil&gas industry).

Among the ongoing EGS projects worldwide, the Soultz European pilot site is in the most advanced stage, providing already an invaluable data base. A critical aspect of the EGS technology addresses the seismic hazards induced by the hydraulic fracturing process. Commercial exploitation in Europe has already started in Germany and the UK but these are at 3-10MWe scale. The driving force is the large potential for non hydrothermal countries and the financial tariff proposed by some Member States. EGS has large potential and much wider applications for many of the EU countries.

EGS technology is also being applied to hydrothermal projects to maintain sustainability by reinjection and expansion of exploitation to the hot dry field outside the periphery of the hydrothermal reservoir.

EGS is the technology to move the industry from a resource base industry (targeting the most productive spots) to an engineering based industry (capable of reproducing installations reliably and consistently in all sorts of geologic environments).
• **Cascade use benefits**

The possibility (present only for geothermal energy among all the other renewable ones) of an integrated exploitation of electricity and heat through a cascade approach, is a key element for the success of the technology and for its penetration deeply in the energy market. The cascade utilization increases the overall utilization of the geothermal energy from the same infrastructure of wells, resulting in a better total efficiency and important economical benefits. The following are only the most important cascade applications present in today’s market. Depending on the source temperature, electricity generation may be not present in the scheme, even if the heat content of the fluid is exploited in steps.

- Power generation
- District heating and cooling
- Industrial processing
- Greenhouses, fisheries
- De-icing, tourism, spa bathes

✈️ **1.2.2. European geothermal industry stakeholders**

**Direct players**

- Municipalities: e.g. Unterhaching
- Utilities: Major (ENEL, EnBW, RWE), regional (ES, Pfalswerke)
- Private developers: e.g. GeoEnergie Bayern, Exorka, EGS Energy, Petratherm, Geothermal engineering ltd, Martifer...
- Subsurface suppliers: consultants, drillers, services companies, suppliers
- Surface suppliers: consultant, engineers, electricity suppliers, turbine and turn-key binary plants manufacturers, contractors
- Public institutes: Geological surveys, Universities, Research Institutes, policy makers and regulators
- Financial services, lawyers, insurances

**Indirect geothermal electricity stakeholders**

- Cascade users of heat
- Civil, works and electro-mechanical contractors for whom smaller plants (compared with fossil fuel or nuclear) may mean easier access to the market.

**Stakeholders expected to join the geothermal market**

- Oil and gas companies (Total, Shell, BP, Wintershall, Statoil),
- Other power utilities (EDF, GDF Suez, Dalkia, etc),
- Large engineering firms (e.g. Technip, Dornier, etc).

All of them have a role to play and effort should be made to involve them.
1.3 To 2020: Laying the foundations of a European geothermal industry

- **Hydrothermal** (high enthalpy resources, flash/dry steam plants)
  - Development in Italy, Greece and ultra peripheral regions (Guadeloupe, Martinique, Azores, Canary Islands, etc) to get the most of the existing exceptional resource (Iceland) and be used as a show case and base for export in other hydrothermal regions.
  - Development of projects in & out of Europe to leverage industry capabilities in terms of exploration, project management, financing capability, etc

- **Hydrothermal** (medium enthalpy resources, binary plants)
  - On medium and low enthalpy resources (e.g. Continental basins, regions with Neogene volcanism)
  - Or in combination with steam or flash plants on high enthalpy resources
  - Hybrid plants (Geothermal + waste heat or biomass or solar thermal or gas) to optimize efficiency, repeatability and consistency and minimize uncertainty of well heat flux when ordering the surface equipment.

- **EGS** (with binary plants)
  - Continue development of commercial demonstration plants to validate the concept in all conditions by governmental incentives (feed-in tariffs, green certificates) and risk mitigation schemes (insurances)
  - Increase plant size to optimize cost (exploration, drilling, site, etc)
  - Establish the base for a financial costing model
  - Establish the basis for a European model of EGS plant:
    - All wells starting from a single drilling pad to minimize surface impact during drilling and operations.
    - Minimal surface occupation (possibly water cooled rather that air), building integration
    - Maximize cascade use with innovative proposal for optimal economical and social benefits
    - Possible combined source of heat (waste heat, solar thermal, biomass or gas) to optimize efficiency, repeatability and consistency and minimize uncertainty of well heat flux when ordering the surface equipment.
    - Possible use of CO2 as a geothermal fluid
    - Master induced seismicity
  - Experiments on supercritical EGS
• **Eliminating mining risk: Exploration**

Sometimes there is competition between geothermal use and other use of subsurface resources like oil and gas exploration and production, gas storage, carbon sequestration, or mining activities as well as some concerns about environmental impacts and in particular micro-seismicity associated with all subsurface activities. Therefore authorities should launch or optimize regional subsurface exploration programs, going as deep as possible to clearly identify all possible usage of the resources and allocate them in the best interest of the community. Resources allocation may be decided after debates and tendering with schedules and commitments. Such effort would further minimize the main investment risks and act as a strong incentive for private investors.

These geothermal resources surveys (exploration plans) may be managed by national geological surveys (or Universities, Research Institutes etc.) when they have the capabilities, if not they could be outsourced to other GSs or private companies. Financing by the authorities (regional, national or European) may be the only way to make sure data are evenly shared to guarantee a fair resource allocation.

Exploration should include the development of a network of dense seismic monitoring networks, to get a better understanding and mastery of possibly induced seismic phenomenon as well as identifying and avoiding high risk areas.

---

**1.4 To 2030: Making EGS a competitive source of Electricity**

• **Hydrothermal**

In 2020, it is very likely that a considerable part of hydrothermal resources in Europe will be exploited, and the European industry should also seek potential development opportunities in other countries blessed with such resources, but with less technical and financial capabilities to develop projects by themselves. This will be the continuation of the move already started in the previous period, and experience gained in the early days will certainly be very valuable (e.g. ENEL or Icelandic companies). Binary plants, possibly in combination with traditional steam or flash plants shall be the standard for optimal use of heat.

• **EGS**

EGS plants should be present all over Europe and in various places in the world by governmental incentives to compensate for the higher drilling cost and lower heat flux, the challenge is now to bring the cost down to be competitive with other comparable sources of energy.

Technology development in exploration, drilling and well optimization should improve ability to detect from surface the most promising zones (naturally open fractures), predict and optimize fracture propagation, locate the next wells and eventually get the necessary high flow and temperature to make projects viable. Technology should also allow to possibly target deeper zones at higher temperature (higher heat flux as well as increased conversion ratio).

Progress in the engineering, design and number of wells per project also has dramatic effect of drilling costs (in the oil and gas drilling there is commonly a 40% reduction in drilling cost between the first and the 5th or 6th well for a project done by the same team in the same location). This will be an immediate benefit for the size increase of projects, in the mean time novel technologies (spaliation, laser, etc) may also bring additional benefits, especially for ultra deep wells, as well as research made by the oil and gas industry for the drilling in hard rocks.
In the mean time, it is expected that fossil fuel electricity production costs increase both from the effect of fuel price and from the obligation to avoid carbon emissions (CCS is expected to increase electricity price by 25 to 30% compared with present situation, due to a combination of higher fuel demand and higher plant cost).

In terms of cost, the estimated current cost of EGS electricity generation from the first-generation prototype plants is of the order of € cent 20-30/kWh. A continued reduction in cost through innovative developments, learning curve effects and co-generation of heat and power should lead to an electricity cost of around or 5 euro cents /kWh. A dry steam power plant today produces electricity at ca. 5 eurocent / kWh, a flash power plant at 8 euro cents / kWh and a Binary-ORC systems at 10 euro cents / kWh. Industry believes that this cost can be reduced by more than 25% by improving drilling technologies and through better resource identification.

1.5 **Beyond 2030: Powering Europe and the World from Geothermal**

- **Hydrothermal**

In 2030, most hydrothermal resources shall be sustainably exploited in Europe and in most countries. The market will be mainly related to the maintenance of existing capacities: work-over and replacement of existing wells, improved surface equipment with higher efficiency. However by 2030 the geothermal market for geothermal production should be EGS.

- **EGS**

By 2030, EGS should be a mature technology capable of providing a reliable, sustainable and competitive source of energy in all areas. The challenge will be the implementation of replacing the existing ageing power production infrastructures all over Europe.

At present, one of the bottlenecks for geothermal development is the lack availability of drilling rigs and subsequently the cost of drilling. To reach an objective of 100 GWe by 2050, an average of additional 25 drilling rigs dedicated to geothermal should be brought to the European market every year between now and 2050, resulting in more than 1000 drilling rigs dedicated to geothermal development by 2050. This is a very large number when compared with the 5 to 10 rigs currently involved in geothermal activity in Europe today, but comparable to the 3500 rigs operating worldwide for the oil and gas industry.

This means the manufacturing of the rigs but also the development of all associated services representing a big challenge for recruitment and training but also a major opportunity for job creation. Geothermal electricity resources have the potential to supply at least 20% of Europe Global Electricity consumption in 2050. The technology is available which should be proven all over Europe in various geological conditions by 2020 and become competitive with other sources by 2030. For large scale development there is a need for defining a roadmap and concrete objectives to be put in place by the authorities, to make things happen at this scale.
2. Strategic Research Agenda for Geothermal Power Generation Technology
2. Strategic Research Agenda for Geothermal Power Generation Technology

2.1 Introduction

Electric power is usually generated exploiting hydrothermal systems. However the most interesting option for the future relies on the exploitation of Enhanced Geothermal Systems (EGS). A major feature of electricity generation by geothermal source is that the technology adopted in the conversion power plant must be tailored on the geothermal fluid available at the surface. Two different extreme situations exist as far as the geothermal fluid is concerned: i) geothermal fluid as dry steam ii) geothermal fluid as liquid brine. The typical conversion technology adopted for the first case is direct steam cycle, while in the second case a binary cycle (i.e. a closed cycle where a working fluid different from the geothermal fluid is employed) is applied. In the intermediate situations, when the geothermal fluid is constituted by a mixture of steam and liquid, or when the geothermal fluid is all liquid at high temperature, a flash steam cycle is usually adopted.

As of 2009, the total installed world electric capacity from hydrothermal systems is as follows: dry steam 3 GW, flash steam 6 GW, binary 1 GW; however, as the yet unexploited geothermal potential relies mostly on liquid sources, a broad diffusion of the binary cycle technology is expected.

The feasibility of commercial power generation from enhanced geothermal systems (EGS) has been proven by the geothermal power plant of Soultz, France, pictured in figure A-1.

Figure A-1: EGS binary power plant of 1.5 MWe capacity at Soultz, France
2.2 Technology state of the art

**Production Pump Technology**

Submersible pump sets are the most widely used units although gas air lift may be occasionally contemplated, mostly for well testing purposes. There are three types of submersible pump designs: (i) electro submersible (ESP), (ii) lineshaft (LSP), and (iii) hydraulically driven (HTP), sketched in figure A-2.

<table>
<thead>
<tr>
<th>Pump type</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP</td>
<td>High submersion depths. Long lifetime. High flow rates in limited casing ID’s (250 m3/hr in 9”5/8). Withstands high temperatures (up to 180-200°C). Solution gas handling (in hole separator). Worldwide service facilities. Can accommodate deviated sections.</td>
<td>Lower efficiency at Soultz (however, the technology has a lot of potential for efficiency increase). Electric insulation shortcomings. Higher costs.</td>
</tr>
</tbody>
</table>

*Figure A-2: Available types of production pumps for geothermal wells*
Problem areas

Challenges essentially concern geopower issues, heat to power, conversion cycles. The upper temperature limits of submersible pumps stand presently at 180°C-200°C. This clearly means that production from high enthalpy resources, the wide majority of which address formation temperatures above 200°C, is bound to vapour lift and related thermochemical (mainly scaling) and well plugging shortcomings, caused by in hole flashing of the geothermal brine.

Status

As of late 2009, most geopower wells operating in the 120-180°C temperature range, eligible to binary (Organic Rankine Cycle – ORC) conversion technology are serviced by downhole pump units of LSP and (to a lesser extent though) ESP types. There are no reports of any HTP operating in these environments although the technology may be regarded as a valuable candidate despite a lower net pump efficiency (hardly 40% against 50-65% for competing ESP and LSP units).

There are over 200 LSPs operating in the western USA, at temperatures and flow rates ranging from 120 to 190°C and 75 to 500 m³/hr respectively by far the presently dominant share in the ORC pumping market, a position likely to be challenged by ESPs as a consequence of both technology developments and industrial force. Among the many available ESP trademarks, the CENTRILIFT and REDA ones belong to two major oil industry service players, Baker-Hughes and Schlumberger; whereas LSP manufacturers are operating in a narrower, ground water, irrigation dominated market.

In EU, two EGS-CHP sites, Soultz and Landau in the Upper Rhine Graben, installed ESPs or LSPs exhibit performance records as follows:

Soultz sous-Forêts (160-165°C WHT)

• 1 LSP unit, rated 35 l/s, set at 350m depth at GPK2 well, undergone 3 pump failures in two years. However, it showed excellent operating efficiency between 54% and 67%.

• 1 ESP, rated 40 l/s, operated at 25 l/s during 12.5 months (effective running time ~3500 hrs, 14 stop/restart cycles). It was set at 500m depth at well GPK4. Due to the low productivity of the well, the ESP operated far from its nominal conditions, which resulted in reduced efficiency, estimated at 34%.

Landau (160°C WHT)

• 1 LSP, rated 80 l/s, set at 360m depth, was operated over two years until change of the former shaft lubricating oil caused undue scaling and further shaft breakage.

Concerned manufacturers highlighted the need for future product development towards 188mm/ 1000HP/ 7000-8000V units, capable of operating in 250°C geothermal environments over a 2-3 years life.

• Binary plants technology

The basic binary plant concept is sketched in figure A-3. Such a binary plant can generate electricity from geothermal sources in a broad range of temperature (down to 100°C or less), it has no need for make-up water and, above all, it is environmentally friendly, having no gas emissions (gases remain dissolved in the all liquid phase). Depending on the source temperature and according to thermodynamic laws, the conversion efficiency decreases at low temperature of the geothermal fluid. The working fluid adopted in the binary cycle differentiates the ORC cycle, which employs an organic fluid (figure A-4) from the Kalina cycle, which in turn employs a mixture of water and ammonia.
The number of production wells and their capacity define the mass fluid flow available from the production wells (one doublet or triplet). The downhole pump (production pump), shown in figure 3, is a key component in order to have overall good performance.

### Adoption of binary technology for EGS systems

The EGS systems which are being developed at the moment, are characterized by the production of liquid brine at a temperature which corresponds to the actual upper limit of exploitation of conventional binary cycle technology (about 180-200°C). The first EGS project is the well known Soultz project, where the energy conversion plant (figures A-1 and A-3) comprises the downhole pumps installed at the two production wells which pump the geo-fluid (brine of 100 g/l salinity) at the surface, and an air-cooled ORC binary unit which converts the heat of the geo-fluid to electricity. After delivering its heat, the geo-fluid is conveyed to the deep reservoir it came from through the reinjection well.

The operation costs are mainly attributed to the electricity consumption at the production pumps, which at Soultz are around 15% of the power output, but even higher values (up to 30%) can occur.
**Flash plant technology**

In conventional high enthalpy hydrothermal systems, where there is plenty of available steam, the dominant technology consists of a flash plant coupled to wet type cooling towers. The production wells deliver two phase fluid, which is separated at the separator in liquid brine and steam. The steam is conveyed to a steam turbine which powers an electricity generator and after the turbine, it is condensed. The steam condensate and the separated liquid brine are reinjected. In case of presence of non condensable gases in the steam, gas extractors are an essential part of the plant, while a gas treatment plant may be required for minimum environmental impact. Flash plants are fairly simple, low cost, high capacity and high temperature solutions.

The flow chart of a typical geothermal flash plant is shown in figure A-5, while a view of a state-of-the-art such plant is shown in figure A-6. The main components of a geothermal flash plant are the production well field and pipelines, the steam separation and washing system, the brine and condensate reinjection system including pipelines and wells, the power generation unit and gas extraction equipment, as well as the control and coordination of steam supply with power demand and plant transients.

In case of high H2S concentration in the steam, the non condensable gases instead of the cooling tower are conveyed to a gas treatment plant for mercury removal and oxidizing H2S to SO2 which is scrubbed by steam condensate from the cooling towers. A view of the AMIS gas treatment plant developed by ENEL is shown in figure A-7.
Flash steam plants represent quite mature technology, whereby the essential technical components are currently adapted for use in geothermal from well understood parameters of fossil fuel power plant design. Geothermal power plants tend to be smaller distributed power plants, and all such plants are characterized of low pressure (i.e. below 30Bar inlet pressure to the turbine). Market leading geothermal plants have several key features in common which contribute to their success:

- Advanced washing systems that clean and prepare steam before entering the turbine, and in some
cases respond to changes in steam chemistry in real time.

- Last Stage Blades or LSB (i.e. at the turbine exhaust) which are in excess of 30 inches in 50 Hz and 26 inches in 60 Hz. LSB size has a disproportionate value in geothermal steam where a large proportion of the energy conversion is at low pressure, thus larger blades infer a larger swallowing capacity, resulting in a lower specific size and reduced unit cost.

- Use of materials for Geothermal plants, piping and turbines that are based on advanced knowledge, experience and understanding (but which are not necessarily advanced materials in themselves).

- In some cases, multiple flash systems to utilise the steam resource more efficiently.

**Adoption of flash technology for EGS Systems**

Most interesting EGS systems are expected to produce brine at temperature higher than 200 °C: in this case, the flash technology may be applied. This technology, if applied as it is to an EGS system, results in needs for make up water, in order to counter the water lost in the atmosphere due to the evaporation from the cooling towers. In case of proximity to the sea, an alternative option which eliminates this problem and further improves conversion efficiency of the plant, would be the use of a sea-cooled direct water condenser (figure A-8).

![Figure A-8: View of the 15 MWe sea-water cooled Bouillante geothermal power plant in Guadeloupe, France, operating since 1986 in urban environment (Jaudin F. 2006)](image)

The power generated by a flash plant can be increased by adding one or more binary units to the separated brine pipeline, as shown in figure A-9. Depending whether or not a wet cooling tower is used both in the steam plant and in the binary system, the plant still requires make up water for the cooling tower.

A different power plant configuration with dry condensation (hence without water consumption) is shown in figure A-10. It combines a back pressure steam turbine with two groups of binary units, the first one placed at the outlet of the steam turbine (thus realizing a combined cycle), whilst the second one is placed at the separated liquid brine line. A state-of-the-art such plant has been operating for several years now in Rotokawa, New Zealand, pictured in figure A-11.
Note that, in cases of high enthalpy geothermal systems where both the brine temperature and pressure are high enough, there is no need for the production pump whilst the gas extraction and treatment plants are generally required, depending on the geothermal fluid chemistry.

Figure A-9: The addition of a binary plant at the separated liquid line of a flash plant maximizes the electricity generation from the resource.

Figure A-10: Combining a back pressure turbine with binary plants at both the steam and liquid lines results in optimum efficiency, with no needs for make-up water and minimum environmental impact.
Dry steam geothermal power plants are the simplest configuration with equipment similar to the one of flash plants, but without the separators and the two phase pipelines, see figures A-12 and A-13. However, dry steam fields are rare geothermal occurrences, as only a handful of such hydrothermal systems have been encountered on earth until now.

The technology and technology development needs of dry steam plants are similar to the ones of flash plants.
2.3 TECHNOLOGY DEVELOPMENT OBJECTIVES

The state of the art of present EGS plants is characterized by medium temperature, low capacity, high capital costs, and high auxiliary power consumption especially at the production pumps. Large scale utilization of EGS would require systems of large capacity with multiple wells, exploiting high temperature resources, improving conversion efficiency, improving downhole pump temperature range and efficiency, using flash technology and reducing costs. Aspects that are also necessary for the success of EGS plants are reliability and public acceptance.

Table A-1: EGS technology development objectives

<table>
<thead>
<tr>
<th>EGS plant’s state of the art</th>
<th>EGS objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>medium temperature</td>
<td>high temperature</td>
</tr>
<tr>
<td>low capacity</td>
<td>large capacity with multiple wells</td>
</tr>
<tr>
<td>high auxiliary power consumption especially at the production pumps</td>
<td>improving downhole pump temperature range and efficiency</td>
</tr>
<tr>
<td>high capital costs</td>
<td>reducing costs</td>
</tr>
<tr>
<td></td>
<td>improving conversion efficiency</td>
</tr>
<tr>
<td></td>
<td>using flash technology</td>
</tr>
</tbody>
</table>

Technology development objectives are summarized as follows:

- Improving operating efficiency by 20-25% (ENGINE 2008b)
  - Smart ESP downhole pump technology
  - Power plant conversion efficiency and auxiliaries
• Reducing costs by at least 20% (ENGINE 2008b)
  - Integration with district heating/cooling
  - Adapting flash plant technology or high temperature binary to EGS systems
  - Alternative technologies for low cost power generation from low temperature resources

• Improving reliability
  - High temperature (250-300°C) ESP pump
  - Inhibiting scaling and corrosion

• Improving acceptance
  - Environmental impact

• Combining EGS with CSS
  - CO₂ as heat carrier fluid

• Production pump technology requirements

Whereas production within the 120-180°C temperature range seems well secured thanks to current LSP and ESP technologies, the 200 to 300°C gap needs to be bridged in order to cover most of the industry demand in the field of hydrothermal and EGS resource developments.

The 250°C target for ESP pumps should be likely met by the industry in the coming 2010-2020 decade.

Owing to entirely new component and material designs achievement of the 300°C target should require ten more years on present tool development trends, unless otherwise dictated by development priorities [deep/ultra deep (10 km) hydrocarbon accumulations, enhanced, geothermal reclamation policies, and others] in which case the ten year maturation period could be shortened to five years (2015 horizon).

It is recalled here that downhole pump sustained production avoids in hole brine flashing, therefore preventing undue well and production damage is indeed a key issue. Keeping the produced fluid under pressure, thus avoiding flashing in hole and related thermo chemical damage, should undoubtedly meet geopower reliability requirements (and hence costs per unit electricity delivered), a constant, insistent, demand of geothermal players in a competing energy market.

Although quantifying the impact of a downhole pump on power plant input/output ratings remains a highly site specific exercise, it can be inferred with fair reliability that owing to well work over and surface equipment maintenance savings (resulting in both plant utilisation factor and well deliverability upgrading) should achieve 10 to 15 % resulting gains from present productivity figures. Noteworthy is that artificial lift sustained production is deemed to have more impact on the annually generated energy than the installed capacity which results from the improved reliability of the plant due to the avoidance of downhole or in-rock scaling.

• Binary plant technology requirements

The ORC is a proven and commonly adopted technology for geothermal applications with medium low temperature sources. More than 170 units are installed in the world, but this technology is not yet commonly used in the EU for geothermal applications, despite the high potential for EGS and hydrothermal systems. The construction of commercial/utility scale plants, as presently ongoing in Germany, is the
most effective means to pave the way for a faster diffusion and refinement of this technology.

Binary cycle conversion efficiency is bound for thermodynamic reasons to the temperature of the heat sources: higher efficiency is to be expected with higher temperature geothermal fluid (and lower temperature cooling fluid), as noticeable from figure 14.

Nevertheless, plant conception, selection of working fluid and design of components have a relevant impact on the overall performance.

Technology requirements to increase the performance concern the following fields:

• Selection and testing of suitable working fluids and blends (zeotropic mixtures)
• New refrigerants with very small GWP (Global Warming Potential) potentially to be available; applicability to ORC turbogenerators should be investigated and checked in real plants.
• Increase in the turbine efficiency (through continuous improvements in thermo-fluid-dynamic, finite element and vibration analysis)
• Thermodynamic cycle optimization and increase in cycle efficiency (multi level, multi fluid, supercritical, optimized extraction of the heat for combined heat and power)
• Reduction of the specific cost/kW (by increasing power plant size; by the adoption of more efficient heat exchangers)
• Improvement in plants’ reliability through the introduction of diagnostic devices for scaling and leakage in the heat exchangers
• Air condensers – the most common used type of cooling in geothermal ORC’s - are the largest and single-item most expensive components in a geothermal ORC plant; further development to optimize performance as well as to reduce noise and size are still possible spraying of water (if available) in hot conditions is also an interesting way to increase performance

![Figure A-14: Measured values of conversion efficiency for geothermal binary plants as a function of geothermal fluid temperature (Bombarda 2009).](image)

• Flash and dry steam plant technology development needs

**Turbine Washing System** - Geothermal steam, being both wet and with aggressive chemistry, presents many problems for conventionally designed turbines. Scaling of the turbine is still one of the main drivers for turbine overhaul. Cleaning and preparation of the steam can improve the chemistry and extend the time between major overhauls. However, clean steam often comes at the price of reduced enthalpy in
the main flow. Improved methods of removing minerals and non condensable gases from the main steam flow are likely to be justifiable.

**Turbine - Last Stage Blade**, conventional design rules suggest that increasing the LSB size and exit diameter from the turbine will result in improving economies of scale. Stress Corrosion Cracking (SCC) in the last stage blade is often cited as the limiting factor in the blade length (due to the reduction in stress levels that are required) however erosion due to water droplets is also a factor that limits size. Improved methods of countering SCC would undoubtedly lead to increased LSB sizes. Titanium blades have been developed by some leading manufacturers in the industry, displaying improved corrosion resistance. However these have not gained widespread acceptance due to concerns about their performance in relation to erosion resistance.

**Small turbines** - At the opposite end of the spectrum, there is reputedly intriguing ongoing work to develop small, 'high speed' turbine wheels that rotate at tens of thousands of RPM a concentrated power extraction. Clearly the benefits here would be reductions in materials usage, although questions remain about use of such devices with wet steam that would cause erosion. Recently, within the indirect geothermal market (i.e. non flash) such turbo-expanders are commonly used with binary fluids.

**Condensers and Piping** - Direct contact condensers (DCC) are widely used within geothermal, and of the major manufacturers, there exists one type of advanced high performance units, and hence result in compaction and theoretically lower costs. However, for all DCC’s the use of stainless steel is prevalent to prevent corrosion and it has been suggested that internal plastic coating could effectively combat corrosion and reduce the need for stainless steel in certain key areas. The same could potentially apply to areas of piping where stainless steel is currently used but a lower grade of steel with coated surfaces could be applied. This is certainly a specific area of research that the geothermal power plants manufacturer Alstom is planning to pursue at the first opportunity.

**Heat Exchangers for Indirect Solution** - Probably the area where there is most commercial uncertainty (and potentially best use of outside funding) is to develop heat exchangers that could be used in geothermal for indirect power plants, either binary or steam. Indirect Cycles show some efficiency benefits, however the heat exchangers are costly and conventional designs prone to fouling. Shell and tube is conventionally used, but plate and frame standards could lead to cost benefits and flexibility during maintenance. The USA market is driven by efficient long term payback calculations and so there is the prospect of some uplift in installation costs being acceptable for a medium pay-back improvement. This could have the potential to replace conventional flash designed power plants altogether in certain markets.

**Seismic design** - Geothermal power plants are almost always sited in areas of high seismicity and hence many of the structures require to be over-engineered as a result. Thus scope exists to examine very closely where components could be made lighter or more resistant to seismic activity without increasing the cost unduly, as is currently the case.

**Cycle design** - Advanced thermodynamics for geothermal is of benefit in early stage site analysis. Development of tools to assist this is an important part of R&D research for Alstom.

• Other low cost power generation plants for low temperature resources

Other than ORC or Kalina technologies for low temperature power generation are available, some of which are already used in ocean energy, heat recovery and heat exchangers. Their use for geothermal power conversion provides significant opportunities for costs reductions.


2.4 Research Priorities

• Downhole pump

Downhole pump research priorities include improvement of ESP technology in terms of both efficiency and ability to handle higher temperature (250-300°C) saline water, as production pumping corresponds to a large part of internal energy needs of an EGS power plant. Improvements in pump efficiency, reliability, operation temperature range and corrosion resistance are of top priority for further research.

• Surface heat transport from the wells to the power plant

R&D needs should also include improving reliability of surface equipment, improving efficiency of surface pumps, and developing new innovative scale and corrosion inhibitors and methods. Improving high temperature water and/or steam pipeline technology in terms of corrosion resistance may reduce surface equipment costs.

• Binary Power Plants

Even if major expectations for geothermal electricity are related to the exploitation of EGS systems, still a considerable interest relies on the exploitation of low temperature geothermal sources, which are broadly distributed and do not require to be engineered. In both cases the technology to be applied is the binary plant technology: advances in this technology are therefore fully beneficial to geothermal development.

Concerning binary plants, development includes design of high efficiency and low parasitic losses plants, utilizing new working fluids and improved cycle schemes. Reengineering geothermal binary plants can provide further heat to power conversion efficiency by 10% resulting in 10% more useful energy output from the same system and 5-10% lower costs of geothermal electricity. For example, improving the refrigerant distribution at the evaporator, and using counter flow heat exchangers will result in higher heat exchange efficiency and higher temperature at the turbine inlet, and in turn in higher heat to power conversion efficiency, or more electricity delivered for a small increase in capital costs.

Kalina plants need further improvement in terms of unit costs, reliability and conversion efficiency, as well as in eliminating any ammonia leaks to zero (sealing materials and technology).

ORC plant costs can be effectively reduced by reducing the size of the components (less material cost) and exploiting synergies with other industries such as the heat pump industry (less cost for components due to economies of scale). For example, a critical parameter is the working fluid selected, where the heat pump industry trends lead to R134a and R410A, which have better heat transfer properties and higher operating pressure. Better heat transfer properties result in smaller heat exchangers, while higher operating pressure leads to smaller turbines and piping equipment. This may require the development of turbines for the above fluids and pressures, while using standardized heat exchangers from the heat pump industry.

Interesting economic performance can also be obtained with combined heat and power plants or hybrid systems. In the first case, thermal power is produced by the plant together with electric power, while in the second case the geothermal source is coupled to a second energy source, which could be as well a renewable source or a residual heat. In both cases, in order to satisfy all the constraints, a complex thermodynamic cycle is most likely required (for example a cascaded cycle) therefore the optimization of the plant operating becomes crucial in order to have the best economic performance; in this frame, convenience of adopting a variable inlet nozzles turbine should be evaluated.
Furthermore, the development of high temperature, high performance downhole pumps for EGS systems and the significant benefits induced by the avoidance of downhole scaling and environmental impact could also extend the actual range of convenient binary cycle application (now commonly 180-200°C, see figure 14) versus higher geothermal brine temperatures. High temperature application of the downhole pump is actually deemed feasible if the pump is cooled (Bombarda and Gaia 2005).

Though binary plant technology is not bound by any temperature limit in the range of currently expected temperature for EGS geothermal fluids (common biomass applications are up to the temperature of 300°C), adoption of flash or combined cycle technology in EGS plants should be investigated as well.

• Flash and dry steam plants

The flash plant technology development needs analyzed above are evaluated in terms of expected impact in table A-2. Estimated costs and timescale for developing above technologies are presented in table A-3.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Feasibility</th>
<th>Energy efficiency</th>
<th>Additional MW</th>
<th>Cost reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine washing</td>
<td>medium</td>
<td>low</td>
<td>low</td>
<td>High (through reduced overhaul)</td>
</tr>
<tr>
<td>Turbine LSB</td>
<td>high</td>
<td>Medium/high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Small Geo Turbines</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
<td>Medium with high potential</td>
</tr>
<tr>
<td>Condenser &amp; piping material</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>medium</td>
</tr>
<tr>
<td>Indirect heat exchangers</td>
<td>Medium/high</td>
<td>high</td>
<td>medium</td>
<td>Low/none</td>
</tr>
<tr>
<td>Seismic design</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Cycle design tools</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
</tbody>
</table>

Table A-3: Time and financial resources needed for achieving the flash plant technology development objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Feasibility</th>
<th>Energy efficiency</th>
<th>Additional MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine washing</td>
<td>7</td>
<td>18</td>
<td>500</td>
</tr>
<tr>
<td>Turbine LSB</td>
<td>11.5</td>
<td>18</td>
<td>2000</td>
</tr>
<tr>
<td>Small Geo Turbines</td>
<td>5.5 - 11.5</td>
<td>48</td>
<td>5000</td>
</tr>
<tr>
<td>Condenser &amp; piping material</td>
<td>7</td>
<td>24</td>
<td>300</td>
</tr>
<tr>
<td>Indirect heat exchangers</td>
<td>8</td>
<td>24</td>
<td>500</td>
</tr>
<tr>
<td>Seismic design</td>
<td>8</td>
<td>12</td>
<td>250</td>
</tr>
<tr>
<td>Cycle design tools</td>
<td>10</td>
<td>24</td>
<td>250</td>
</tr>
</tbody>
</table>

• Other technologies

R&D needs to include adoption of other power generation technologies in low temperature resources, as a means of improving the competitiveness of low temperature geothermal power generation.


2.5 Roadmap for 2020/2030/Beyond

• Short-term research

Technology development for the next 5 years should focus on developing a high temperature ESP downhole production pump for 250°C fluids of high salinity and considerably improving its efficiency over a wide spectrum of operating conditions (flow rate and head), in order to use it in the new EGS projects under development, as well as further advancing binary plants technology in terms of conversion efficiency and costs.

Increase in binary plant efficiency and flexibility can be pursued in the short term through development and ground validation of multi level and supercritical cycle plants.

Short term research priorities for geothermal flash plants should include cycle design tools, seismic design, innovative condenser and piping materials, indirect heat exchangers and improved turbine washing systems, as explained in chapters §2.3 and §3.4, and evaluated in terms of expected impact over estimated R&D costs.

Short term technology development activities should also include investigating the feasibility and demonstrating other technologies for competitive low temperature geothermal power generation.

• Medium-term research

Technology developments for the next 10 years (until 2020) should aim at increasing the capacity of EGS plants by at least one order of magnitude (from 1-5 MWe to 30-100 MWe), adapting flash plant technology to EGS needs, developing new combined heat and power plants utilising the heat rejected from the power plant condenser for district heating, as well as further improving costs, conversion efficiency, plant reliability and environmental footprint.

Binary plants trend concerning increase of conversion efficiency and reduction of costs shall be pursued and stimulated. Consistent improvements in heat exchangers’ efficiency and reliability which would in turn improve binary plants’ cost effectiveness, are at reach for the medium term.

Concerning flash steam plants, medium term research should focus on the most resource consuming items of chapter §3.4, which also have the highest potential impact. These are improving turbine last stage blade and development of small high speed turbines for geothermal steam.

• Long-term research

Long-term technology development should include:

• Reducing overall plant costs, so that EGS plants capital costs converge to the capital costs of present geothermal flash power plants, which for a >100 MWe plant powered by high enthalpy fluids from 2-3 km deep wells is around 1.2-1.35 million euro per installed MWe (Mighty River Power 2009, McLoughlin et al 2010).

• Further increasing the temperature ceiling of downhole production pumps to 300°C or even higher.

• Examining the feasibility and using alternative heat carrier fluids such as carbon dioxide.

• Development of high temperature geothermal power plants, suitable for the exploitation of ultra deep (>5 km depth), supercritical, or magma resources (>400°C).
3. References Geothermal Electricity
3. Reference: Geothermal Electricity


ENGINE (2008a). Best Practice Handbook for the development of unconventional geothermal resources with a focus on enhanced geothermal systems. Available at the web site http://engine.brgm.fr/

ENGINE (2008b). Propositions for the definitions of research areas on enhanced geothermal systems. Available at the web site http://engine.brgm.fr/


