Technology Roadmap

Geothermal Heat and Power

International Energy Agency

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

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- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of CO_2 will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We must – and can – change our current path; we must initiate an energy revolution in which low-carbon energy technologies play a leading role. If we are to reach our greenhouse-gas emission goals, we must promote broad deployment of energy efficiency, many types of renewable energy, carbon capture and storage, nuclear power and new transport technologies. Every major country and sector of the economy must be involved. Moreover, we must ensure that investment decisions taken now do not saddle us with suboptimal technologies in the long term. There is a growing awareness of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is developing a series of roadmaps for key energy technologies. These roadmaps provide solid analytical footing that enables the international community to move forward, following a well-defined growth path – from today to 2050 – that identifies the technology, financing, policy and public engagement milestones needed to realise the technology's full potential. The IEA roadmaps include special focus on technology development and deployment to emerging economies, and highlight the importance of international collaboration.

Geothermal energy today is mainly known for its reliable production of base-load power – the power needed to meet minimum demands – in areas where geological conditions permit fluids to transfer heat from the Earth to the surface in self-flowing wells at high temperatures. However, geothermal resources at moderate temperatures can be found in aquifers that are widespread. Such resources can be used in binary power plants, combined heat and power plants or in heat-only applications. Emerging geothermal technologies that extract energy from the hot rock resources found everywhere in the world hold much promise for expanding the production of geothermal power and heat.

This roadmap envisions that by 2050, geothermal electricity generation could reach 1 400 TWh per year, *i.e.* around 3.5% of global electricity production. Geothermal heat could contribute 5.8 EJ annually by 2050. For geothermal energy for heat and power to claim its share of the coming energy revolution, concerted action is required by scientists, industry, governments, financing institutions and the public. This roadmap is intended to help drive these necessary developments.

Nobuo Tanaka
Executive Director, IEA

This roadmap was prepared in 2011. It was drafted by the IEA Sustainable Energy Policy and Technology directorate. This paper reflects the views of the International Energy Agency (IEA) Secretariat, but does not necessarily reflect those of individual IEA member countries. For further information, please contact: technologyroadmapscontact@iea.org

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Acknowledgements

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Key findings

Geothermal energy can provide low-carbon base-load power and heat from high-temperature hydrothermal resources, deep aquifer systems with low and medium temperatures, and hot rock resources. This roadmap envisages development and deployment of geothermal heat and power along the following paths:

- By 2050, geothermal electricity generation could reach 1 400 TWh per year, *i.e.* around 3.5% of global electricity production, avoiding almost 800 megatonnes (Mt) of CO_2 emissions per year.
- Geothermal heat[1] could contribute 5.8 EJ (1 600 TWh thermal energy) annually by 2050, *i.e.* 3.9% of projected final energy for heat.
- In the period to 2030, rapid expansion of geothermal electricity and heat production will be dominated by accelerated deployment of conventional high-temperature hydrothermal resources, driven by relatively attractive economics but limited to areas where such resources are available. Deployment of low- and medium-temperature hydrothermal resources in deep aquifers will also grow quickly, reflecting wider availability and increasing interest in their use for both heat and power.
- By 2050, more than half of the projected increase comes from exploitation of ubiquitously available hot rock resources, mainly via enhanced geothermal systems (EGS).[2] Substantially higher research, development and demonstration (RD&D) resources are needed in the next decades to ensure EGS becomes commercially viable by 2030.
- A holistic policy framework is needed that addresses technical barriers relating to resource assessment, accessing and engineering the resource, geothermal heat use and advanced geothermal technologies. Moreover, such a holistic framework needs to address barriers relating to economics, regulations, market facilitation and RD&D support.
- Policy makers, local authorities and utilities need to be more aware of the full range of geothermal resources available and of their possible applications. This is particularly true for geothermal heat, which can be used at varying temperatures for a wide variety of tasks.
- Important R&D priorities for geothermal energy consist of accelerating resource assessment, development of more competitive drilling technology and improving EGS technology as well as managing health, safety and environmental (HSE) concerns.
- Advanced technologies for offshore, geo-pressured and super-critical (or even magma) resources could unlock a huge additional resource base. Where reasonable, co-produced hot water from oil and gas wells can be turned into an economic asset.

Key actions in the next 10 years

- Establish medium-term targets for mature and nearly mature technologies and long-term targets for advanced technologies, thereby increasing investor confidence and accelerating expansion of geothermal heat and power.
- Introduce differentiated economic incentive schemes for both geothermal heat (which has received less attention to date) and geothermal power, with incentives phasing out as technologies reach full competitiveness.
- Develop publicly available databases, protocols and tools for geothermal resource assessment and ongoing reservoir management to help spread expertise and accelerate development.
- Introduce streamlined and time-effective procedures for issuing permits for geothermal development.
- Provide sustained and substantially higher research, development and demonstration (RD&D) resources to plan and develop at least 50 more EGS pilot plants during the next 10 years.
- Expand and disseminate the knowledge of EGS technology to enhance production, resource sustainability and the management of health, safety and environmental (HSE) performance.
- In developing countries, expand the efforts of multilateral and bilateral aid organisations to develop rapidly the most attractive available hydrothermal resources, by addressing economic and non-economic barriers.

1. Ground source heat pump technology, also known as "shallow geothermal technology", is not included in this roadmap (see Box 2).

2. Although the preferred wording of EGS is still being discussed, for this roadmap the IEA has chosen to use Enhanced Geothermal Systems, abbreviated as EGS.

Introduction

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of providing clean energy, mitigating climate change and sustainable development. This challenge was acknowledged by the ministers from G8 countries, China, India and South Korea, in their meeting in June 2008 in Aomori, Japan, where they declared the wish to have the IEA prepare roadmaps to advance innovative energy technology.

> *"We will **establish an international initiative with the support of the IEA** to develop roadmaps for innovative technologies and co-operate upon existing and new partnerships, including carbon capture and storage (CCS) and advanced energy technologies. Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognize and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies..."*

To achieve this ambitious goal, the IEA has undertaken an effort to develop a series of global technology roadmaps covering the most important technologies. These technologies are evenly divided among demand-side and supply-side technologies. This geothermal energy roadmap is one of the roadmaps being developed by the IEA.

The overall aim of these roadmaps is to demonstrate the critical role of energy technologies in achieving the stated goal of halving energy-related carbon dioxide (CO_2) emissions by 2050. The roadmaps will enable governments, industry and financial partners to identify the practical steps they can take to participate fully in the collective effort required.

This process began with establishing a clear definition and the elements needed for each roadmap. Accordingly, the IEA has defined its global technology roadmaps as:

> *"... a dynamic set of technical, policy, legal, financial, market and organizational requirements identified by the stakeholders involved in its development. The effort shall lead to improved and enhanced sharing and collaboration of all related technology-specific research, development, demonstration and deployment (RDD&D) information among participants. The goal is to accelerate the overall RDD&D process in order to enable earlier commercial adoption of the technology in question."*

Rationale for geothermal energy

Geothermal technologies use renewable energy resources to generate electricity and/or heating and cooling while producing very low levels of greenhouse-gas (GHG) emissions (Box 1). They thus have an important role to play in realising targets in energy security, economic development and mitigating climate change.

Geothermal energy is stored in rock and in trapped vapour or liquids, such as water or brines; these geothermal resources can be used for generating electricity and for providing heat (and cooling). Electricity generation usually requires geothermal resources temperatures of over 100°C. For heating, geothermal resources spanning a wider range of temperatures can be used in applications such as space and district heating, spa and swimming pool heating, greenhouse and soil heating, aquaculture pond heating, industrial process heating and snow melting. Space cooling can also be supplied

Box 1: Geothermal energy: renewable energy source and sustainable energy use

Geothermal energy is considered renewable as there is a constant terrestrial heat flow to the surface, then to the atmosphere from the immense heat stored within the Earth. Heat can be extracted at different rates. Sustainable use of geothermal energy implies that the heat removed from the resource is replaced on a similar time scale (Rybach and Mongillo, 2006). Practical replenishment (*e.g.* 95% recovery) will generally be reached on time scales of the same order as the lifetime of the geothermal production system. It is suggested that for each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, below which it will be possible to maintain constant energy production from the system for 100 to 300 years (Axelsson, *et al*., 2001).

Box 2: Ground source heat pumps

Ground source heat pumps (GSHP) make use of the stable temperature of the ground, of *e.g.* 10 to 15°C in moderate climates, at a few meters depth in case of horizontal heat exchanger systems and depths of up to 150m for heat pumps using vertical heat exchange boreholes. GSHPs are mainly used in buildings for space heating, cooling and sometimes domestic hot water supply. Heat pumps allow transformation of heat from a lower temperature level to a higher one by using external energy (*e.g.* to drive a compressor). The amount of this external energy input, be it electric power or heat, has to be kept as low as possible to make the heat pump environmentally and economically desirable. In contrast to other heat pumps, such as air-to-air heat pumps, ground source heat pumps can store extracted heat in summer and make this heat useful again in the heating mode in winter.

through geothermal heat, through the use of heat-driven adsorption chillers as an alternative to electrically driven compression chillers.

Even the modest temperatures found at shallower depths can be used to extract or store heat for heating and cooling by means of ground source heat pumps (GSHP, Box 2). GSHP are a widespread application for geothermal energy, especially in colder climates, but they follow a different concept from deep geothermal heat technologies and address a different market, so for reasons of clarity this roadmap excludes them.

Global technical potential for geothermal electricity has been estimated at 45 EJ/yr — 12 500 TWh_e, *i.e.* about 62% of 2008 global electricity generation (Krewitt *et al*. 2009). The same study estimated resources suitable for direct use at 1 040 EJ/yr — 289 000 TWh_t; worldwide final energy use for heat in 2008 was 159.8 EJ/44 392 TWh_t (Ibid.). The estimated technical potential for geothermal electricity and geothermal heat excludes advanced geothermal technologies that could exploit hot rock or off-shore hydrothermal, magma and geo-pressured resources. Although geothermal energy has great technical potential, its exploitation is hampered by costs and distances of resource from energy demand centres.

Geothermal typically provides base-load generation, since it is generally immune from weather effects and does not show seasonal variation.[3] Capacity factors of new geothermal power plants can reach 95%. The base-load characteristic of geothermal power distinguishes it from several other renewable technologies that produce variable power. Increased deployment of geothermal energy does not impose load-balancing requirements on the electricity system. Geothermal power could be used for meeting peak demand through the use of submersible pumps tuned to reduce fluid extraction when demand falls. However, procedures and methods that allow for a truly load-following system have yet to be developed. Geothermal energy is compatible with both centralised and distributed energy generation and can produce both electricity and heat in combined heat and power (CHP) plants.

Geothermal technology development has focused so far on extracting naturally heated steam or hot water from natural hydrothermal reservoirs. However, geothermal energy has the potential to make a more significant contribution on a global scale through the development of the advanced technologies, especially the exploiting of hot rock resources[4] using enhanced geothermal systems (EGS) techniques that would enable energy recovery from a much larger fraction of the accessible thermal energy in the Earth's crust. In the IEA geothermal roadmap vision, geothermal energy is projected to provide 1 400 TWh annually for global electricity consumption in 2050, following the IEA Energy Technology Perspectives 2010 Blue Hi-REN scenario. Geothermal heat use is projected to supply 5.8 EJ/yr in 2050.

3. Air-cooled binary plants are affected by weather since their energy output varies with ambient air temperature.

4. Energy stored in deep rock formations in the Earth where there is little or no fluids is referred to in this roadmap as "hot rock resources". A recent, but not yet widespread, terminology used for this same resource is "petro-thermal resources".

Purpose, process and structure of this roadmap

Geothermal energy can make a significant contribution to meeting global energy needs through continued development of the large hydrothermal resource base and the development of advanced geothermal technologies. The next two decades are a crucial window of opportunity during which EGS will have to be proven in sustainably operated, commercial-scale demonstration plants. Development of conventional hydrothermal resources should also increase, including tapping into markets with abundant resources that suffer from specific constraints. Advanced hydrothermal technologies deserve more attention as well. Geothermal heat use should be exploited on a broader scale, including the use of low- and medium-temperature resources in deep aquifers that may have been overlooked so far.

This roadmap identifies the primary actions and tasks that must be addressed to accelerate geothermal development globally. In some markets, actions are already under way, but many countries have only just started to consider geothermal energy. Accordingly, milestone dates should be considered as indicative of relative urgency, rather than as absolutes.

The IEA first Geothermal Roadmap Workshop (8 April 2010, Paris) focused on technology development. A second workshop (24 October 2010, Sacramento, California) as a side event to the Geothermal Resource Council's annual meeting, focused on the policy framework needed to overcome economic and non-economic barriers. A third workshop (29 November 2010, Bandung, Indonesia) sought to establish conclusions from the first two workshops and a case study of geothermal development in Indonesia.

This roadmap is organised into four parts. It starts with the status of geothermal energy today, focusing on resources, geothermal technology and economics. It continues with a vision for future deployment of geothermal electricity and heat use. Milestones for technology improvements are then described. The roadmap concludes with a discussion of the policy framework required to overcome economic and non-economic barriers and support necessary RD&D.

This roadmap should be regarded as work in progress.[5] As global geothermal efforts advance, new data will provide the basis for updated analysis. Moreover, as the technology, market, power sector and regulatory environments continue to evolve, analyses will need to be updated and additional tasks may come to light.

5. This roadmap is informed by several existing regional and national roadmaps, including: RE-thinking 2050: A 100% Renewable Energy Vision for the European Union" (EREC, 2010); The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century (MIT, 2006); the Australian geothermal roadmap (DRET, 2008); the IPCC Special Report on Renewable Energy's chapter dedicated to geothermal energy (IPCC, forthcoming); Energy [R]evolution: A sustainable World Energy Outlook (EREC/Greenpeace, 2010); and Energy Science & Technology in China: A Roadmap to 2050 (Chinese Academy of Sciences, 2010).

Geothermal energy today

Development of geothermal energy

Although the use of geothermal hot springs has been known since ancient times, active geothermal exploration for industrial purposes started at the beginning of the 19th century with the use of geothermal fluids (boric acid) in Larderello (Italy). At the end of the 19th century, the first geothermal district heating system began operating in Boise (United States), with Iceland following in the 1920s. At the start of the 20th century, again in Larderello, the first successful attempt to produce electricity from geothermal heat was achieved. Since then, installed geothermal electricity has steadily increased.

In 2009, global geothermal power capacity was 10.7 GW_e and generated approximately 67.2 TWh_e/yr of electricity, at an average efficiency rate of 6.3 GWh/MW_e (Bertani, 2010) (Figure 1). A remarkable growth rate from 1980 to 1985 was largely driven by the temporary interest of the hydrocarbon industry – mainly Unocal (now merged with Chevron) – in geothermal energy, demonstrating the considerable influence on the geothermal market of attention from the hydrocarbon sector, which has expertise similar to that needed for geothermal development.

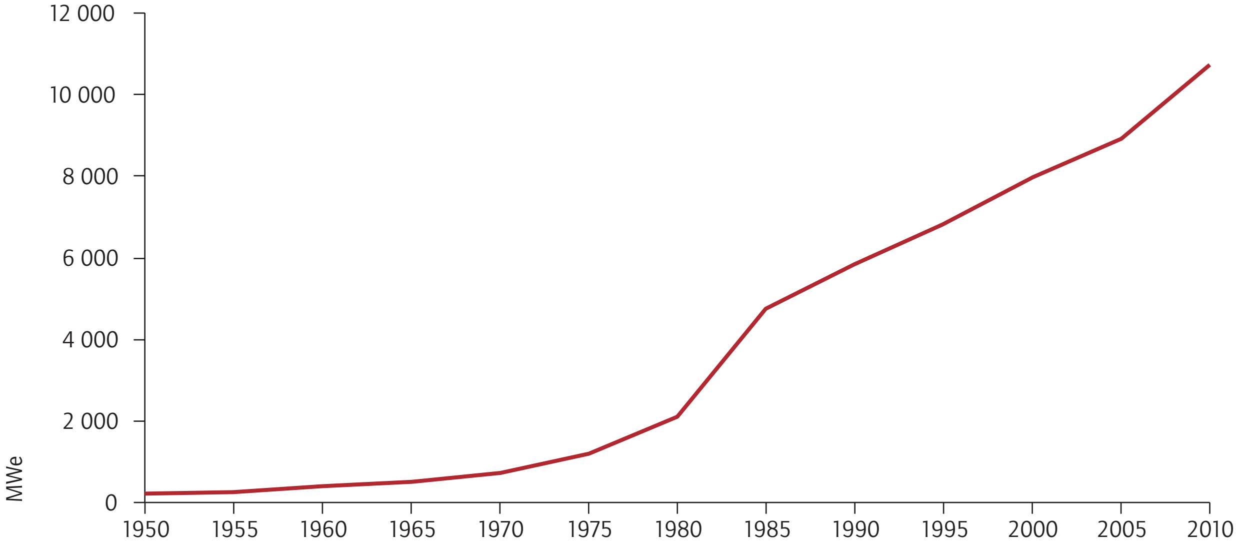
Geothermal electricity provides a significant share of total electricity demand in Iceland (25%), El Salvador (22%), Kenya and the Philippines (17% each), and Costa Rica (13%). In absolute figures, the United States produced the most geothermal electricity in 2009: 16 603 GWh_e/yr from an installed capacity of 3 093 MW_e. Total installed capacity of geothermal heat (excluding heat pumps) equalled 15 347 MW_t in 2009, with a yearly heat production of 223 petajoules (PJ); China shows the highest use of geothermal heat (excluding heat pumps), totalling 46.3 PJ/yr geothermal heat use in 2009 (Lund *et al.*, 2010).

Geothermal resources

Hydrothermal resources

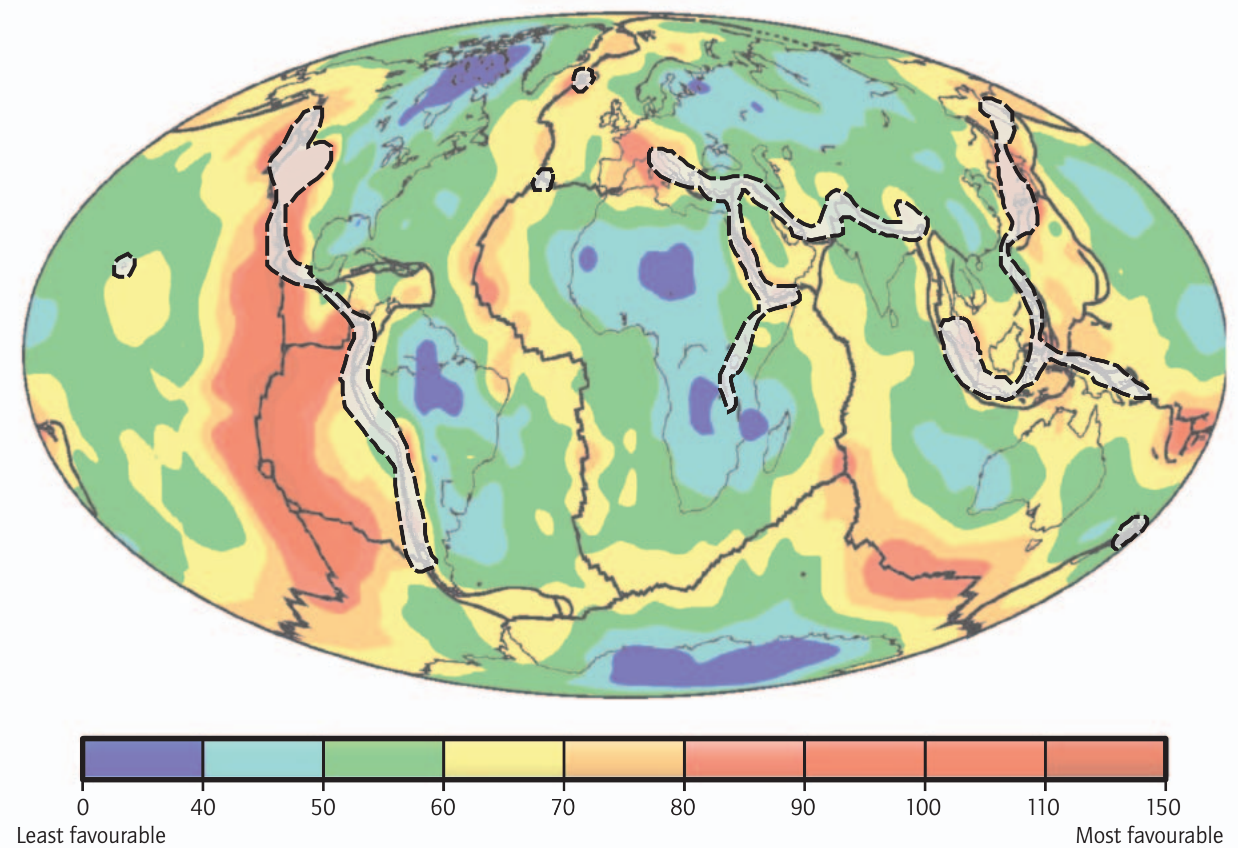
Until recently, utilisation of geothermal energy was concentrated in areas where geological conditions permit a high-temperature circulating fluid to transfer heat from within the Earth to the surface through wells that discharge without any artificial lift. The fluid in convective hydrothermal resources can be vapour (steam), or water-dominated, with temperatures ranging from 100°C to over 300°C. High-temperature geothermal fields are most common near tectonic plate boundaries, and are often associated with volcanoes and seismic activity, as the crust is highly fractured and thus permeable to fluids, resulting in heat sources being readily accessible (Figure 2).

Figure 1: Global development installed capacity geothermal power (MW_e)



Source: Bertani, 2010.

Figure 2: World resource map of convective hydrothermal reservoirs



Note: Convective hydrothermal reservoirs are shown as light grey areas, including heat flow and tectonic plates boundaries.

Source: Background figure from (Hamza *et al.*, 2008), adjustments from (IPCC, forthcoming).

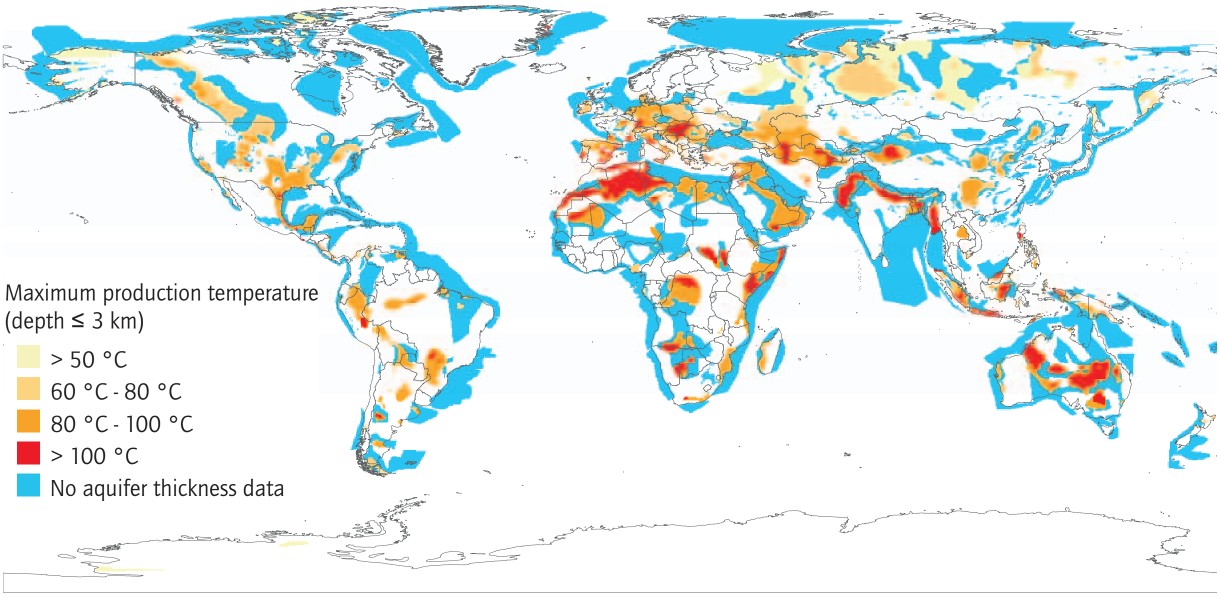
Most plate boundaries are below sea level. There are 67 000 km of mid-ocean ridges, of which 13 000 km have been studied, and more than 280 sites with submarine geothermal vents have been discovered (Hiriart *et al.*, 2010). Some submarine vents have been estimated to be able to realise capacities ranging from 60 MW_t to 5 GW_t (German *et al.*, 1996). In theory, such geothermal vents could be exploited directly without drilling and produce power by means of an encapsulated submarine binary plant. However, R&D is needed since there are no technologies available to commercially tap energy from off-shore geothermal resources.

Geothermal heat can also be economically extracted from many deep aquifer systems all over the world. Many such locations can be reached within a depth of 3 km, with moderate heat flow in excess of 50 MW/m^2 to 60 MW/m^2 and rock and fluid temperatures of in excess of 60°C (Figure 3).

The actual local performance depends strongly on the natural flow conditions of the geothermal reservoir. Geo-pressured deep aquifer systems contain fluids at pressures higher than hydrostatic.

Water co-produced during oil and gas exploitation is another type of hydrothermal resource. Oil and gas wells can produce warm water that is often seen by operators as a by-product with limited commercial upside. Examples are known of aging oil fields in North America that can produce up to 100 million liters of geothermally heated water per day. This could be turned into an asset by extracting the energy contained in the produced water by means of binary cycle power plants.

Figure 3: World map of deep aquifer systems



Note: World map of deep aquifer systems modified from (Penwell, 1984). Overlain are expected average production temperatures for a depth interval starting at excess temperatures of 40°C relative to surface, and ranging to a maximum depth of 3 km. The map is based on heat flow data from Artemieva (2006) and sediment thickness information from Laske and Martens (1997). Local performance strongly depends on natural heat flow conditions and surface temperature.

Source: TNO, www.thermogis.nl/worldaquifer.

Hot rock resources

So far, utilisation of geothermal energy has been concentrated in areas of naturally occurring water or steam, and sufficient rock permeability. However, the vast majority of geothermal energy within drilling reach – which can be up to 5 km, given current technology and economics – is in relatively dry and low-permeability rock. Heat stored in low-porosity and/or low-permeability rocks is commonly referred to as hot rock resources. These resources are characterised by limited pore space and/or minor fractures and therefore contain insufficient water and permeability for natural exploitation.

Hot rock resources can be found anywhere in the world, although they are found closer to the surface in regions with an increased presence of naturally occurring radioactive isotopes (*e.g.* South Australia) or where tectonics have resulted in a favorable state of stress (*e.g.* in the western USA). In stable, old continental tectonic provinces, where temperature gradients are low (7°C/km to 15°C/km) and permeability is low but with less favorable state of stress, depths will be significantly greater and developing an EGS resource will be less economic.

Technologies that allow energy to be tapped from hot rock resources are still in the demonstration stage and require innovation and experience to become commercially viable. The best-known such technology is enhanced geothermal systems (EGS;[6] Box 3). Other approaches to engineering hot rock resources, which are still at the conceptual phase, try methods other than fracturing the hot rock. Such technologies aim instead to create connectivity between water inlet and water outlet, for example by drilling a sub-surface heat exchanger made of underground tubes or by drilling a 7 km to 10 km vertical well of large diameter that contains water inlet and water outlet at different depths.

A global map of hot rock resources is not yet available, but some countries have started mapping EGS resources, including the United States (Figure 5).

6. Some literature sources refer to EGS as hot dry rock, hot wet rock or hot fractured rock technology. For simplicity's sake, this roadmap uses Enhanced Geothermal Systems in the most inclusive manner possible.

Box 3: Enhanced geothermal systems

Enhanced or engineered geothermal systems aim at using the heat of the Earth where no or insufficient steam or hot water exists and where permeability is low. EGS technology is centred on engineering and creating large heat exchange areas in hot rock. The process involves enhancing permeability by opening pre-existing fractures and/or creating new fractures. Heat is extracted by pumping a transfer medium, typically water, down a borehole into the hot fractured rock and then pumping the heated fluid up another borehole to a power plant, from where it is pumped back down (recirculated) to repeat the cycle.

EGS can encompass everything from stimulation of already existing sites with insufficient permeability to developing new geothermal power plants in locations without geothermal fluids. EGS has been under development since the first experiments in the 1970s on very low permeability rocks, and is also known as hot dry rock technology. On the surface, the heat transfer medium (usually hot water) is used in a binary or flash plant to generate electricity and/or used for heating purposes.

Among current EGS projects worldwide, the European scientific pilot site at Soultz-sous-Forêts, France, is in the most advanced stage and has recently commissioned the first power plant (1.5 MW_e), thereby providing an invaluable database of information. In 2011, 20 EGS projects are under development or under discussion in several EU countries.

EGS research, testing and demonstration is also under way in the United States and Australia. The United States has included large EGS RD&D components in its recent clean energy initiatives as part of a revived national geothermal programme.

In Australia, 50 companies held about 400 geothermal exploration licenses in 2010. The government has awarded grants of approximately USD 205 million to support deep drilling and demonstration geothermal projects. The largest EGS project in the world, a 25 MW_e demonstration plant, is under development in Australia's Cooper Basin. The Cooper Basin is estimated by Geodynamics Ltd to have the potential to generate 5 GW_e to 10 GW_e.

In China, there are plans to test EGS in three regions where the geothermal gradient is high: in the northeast (volcanic rocks), the southwest (volcanic rocks) and the southeast (granite).

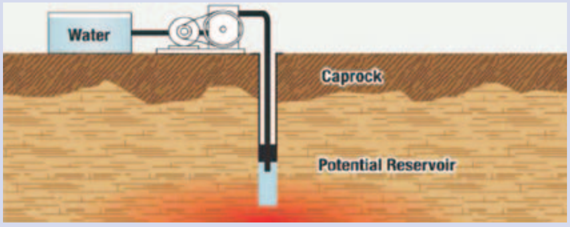
In India, hot rock resources have been estimated to be abundantly available, because of a large volume of heat-generating granites throughout the country, but geothermal energy exploitation has yet to be initiated (Chandrasekharam and Chandrasekhar, 2010).

Box 3: Enhanced geothermal systems (continued)

Figure 4: An enhanced geothermal system in pictures

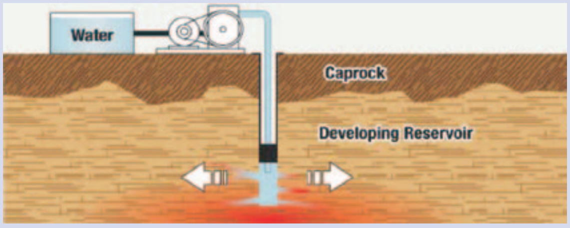
1. Injection well

An injection well is drilled into hot basement rock that has limited permeability and fluid content. All of this activity occurs considerably below water tables and at depths greater than 1.5 kilometre. This particular type of geothermal reservoir represents and enormous potential energy resource.



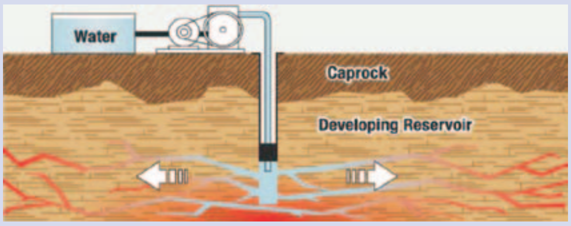
2. Injecting water

Water is injected at sufficient pressure to ensure fracturing or open existing fractures within the developing reservoir and hot basement rock.



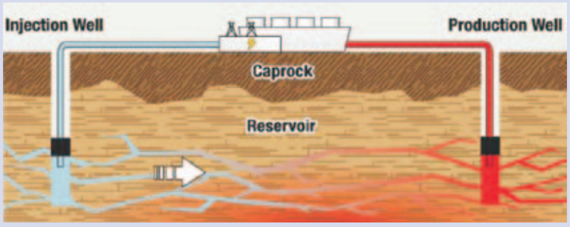
3. Hydro-fracture

Pumping of water is continued to extend fractures and reopen old fractures some distance from the injection wellbore and throughout the developing reservoir and hot basement rock. This is a crucial step in the EGS process.



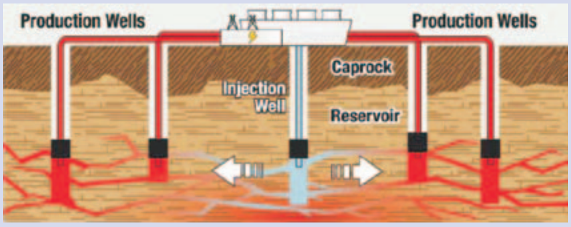
4. Production

A production well is drilled with the intent to intersect the stimulated fracture system created in the previous step and circulate water to extract the heat from the basement rock with improved permeability.



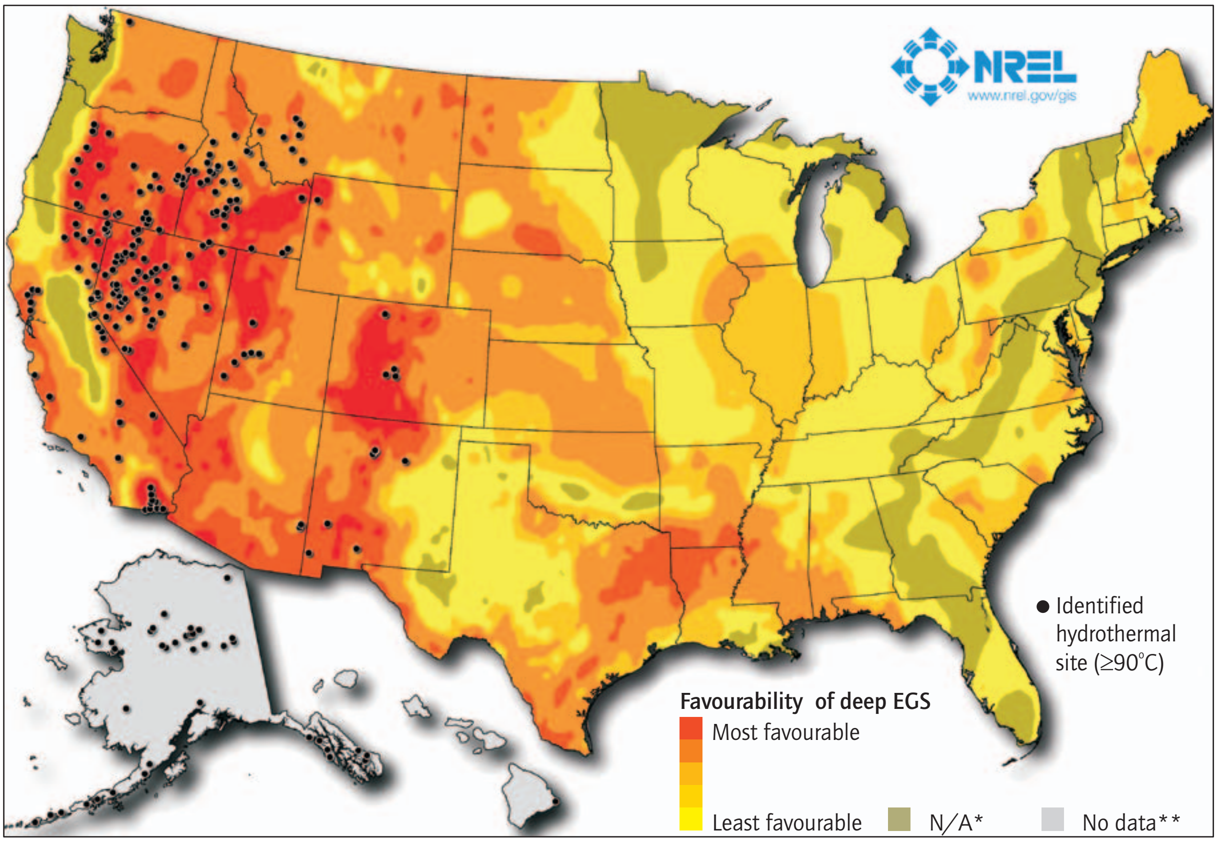
5. Additional production

Additional production wells are drilled to extract heat from large volumes of hot basement rock to meet power generation requirements. Now a previously unused but large energy resource is available for clean, geothermal power generation.



Source: Office of Energy Efficiency and Renewable Energy (EERE) , US Department of Energy.

Figure 5: Geothermal resources in the United States, including favourability of EGS



Source: NREL.

Map does not include shallow EGS resources located near hydrothermal sites or US Geological Survey assessment of undiscovered hydrothermal resources.

Source data for deep EGS includes temperature at depth from 3 to 10 km provided by Southern Methodist University Geothermal Laboratory and analyses (for regions with temperatures ≥ 150°C) performed by NREL.

Source data for identified hydrothermal sites from US Geological Survey assessment of Moderate- and High-temperature Geothermal Resources of the United States (2008).

N/A* regions have temperatures less than 150°C at 10 km depth and were not assessed for deep EGS potential.

No data**: Temperature at depth data for deep EGS in Alaska and Hawaii not available.

Current technologies

Electricity production

Most conventional power plants use steam to generate electricity. Whereas fossil-fuel plants burn coal, oil or gas to boil water, many existing geothermal power plants use steam produced by "flashing" (*i.e.* reducing the pressure of) the geothermal fluid produced from the reservoir. Geothermal power plants today can use water in the vapour phase, a combination of vapour and liquid phases, or liquid phase only. The choice of plant depends on the depth of the reservoir, and the temperature, pressure and nature of the entire geothermal resource. The three main types of plant are flash steam, dry steam and binary plants. All forms of current accepted geothermal development use re-injection as a means of sustainable resource exploitation.

Flash steam plants

The most commonly found geothermal resources contain reservoir fluids with a mixture of hot liquid (water) and vapour (mostly steam). Flash steam plants, making up about two-thirds of geothermal installed capacity today, are used where water-dominated reservoirs have temperatures above

180°C. In these high-temperature reservoirs, the liquid water component boils, or "flashes," as pressure drops. Separated steam is piped to a turbine to generate electricity and the remaining hot water may be flashed again twice (double flash plant) or three times (triple flash) at progressively lower pressures and temperatures, to obtain more steam. The cooled brine and the condensate are usually sent back down into the reservoir through injection wells. Combined-cycle flash steam plants use the heat from the separated geothermal brine in binary plants to produce additional power before re-injection.

Dry steam plants

Dry steam plants, which make up about a quarter of geothermal capacity today, directly utilise dry steam that is piped from production wells to the plant and then to the turbine. Control of steam flow to meet electricity demand fluctuations is easier than in flash steam plants, where continuous up-flow in the wells is required to avoid gravity collapse of the liquid phase. In dry steam plants, the condensate is usually re-injected into the reservoir or used for cooling.

Binary plants

Electrical power generation units using binary cycles constitute the fastest-growing group of geothermal plants, as they are able to use low- to medium-temperature resources, which are more prevalent. Binary plants, using an organic Rankine cycle (ORC) or a Kalina cycle, typically operate with temperatures varying from as low as 73°C (at Chena Hot Springs, Alaska) to 180°C. In these plants, heat is recovered from the geothermal fluid using heat exchangers to vaporise an organic fluid with a low boiling point (*e.g.* butane or pentane in the ORC cycle and an ammonia-water mixture in the Kalina cycle), and drive a turbine. Although both cycles were developed in the mid-20th century, the ORC cycle has been the dominant technology used for low-temperature resources. The Kalina cycle can, under certain design conditions, operate at higher cycle efficiency than conventional ORC plants. The lower-temperature geothermal brine leaving the heat exchanger is re-injected back into the reservoir in a closed loop, thus promoting sustainable resource exploitation. Today, binary plants have an 11% share of the installed global generating capacity and a 44% share in terms of the number of plants (Bertani, 2010).

Geothermal heat use

Heat demand represents a significant share of final energy consumption in cooler regions such as northern Europe, northern USA, Canada and northern China. In warmer climates, heat demand is dominated by industrial process heat, but may still account for a considerable share of energy consumption. Geothermal heat use can cover several types of demand at different temperature levels. Even geothermal resources at temperatures of 20°C to 30°C (*e.g.* flood water in abandoned mines) may be useful to meet space heating demand.

The most widely spread geothermal heat use application, after ground source heat pumps (49% of total geothermal heat), is for spa and swimming pool heating (about 25%), for instance in China, where it makes up 23.9 PJ out of the 46.3 PJ of geothermal heat used annually (excluding ground source heat pumps). The next-largest geothermal heat usage is for district heating (about 12%), while all other applications combined make up less than 15% of the total. The potential for considerable growth in the use of geothermal energy to feed district heating networks should be exploited, both in large, newly built environments and as a replacement for existing fossil-fuelled district heating systems.

Geothermal "heat only" plants can feed a district heating system, as can the hot water remaining from electricity generation, which can also be used in a cascade of applications demanding successively lower temperatures. These might start with a district heating system, followed by greenhouse heating and then perhaps an aquaculture application.

At the time of the oil price peak in 2008, for example, Dutch horticultural entrepreneurs demonstrated that geothermal heat at 60°C could cover 60% to 90% of the energy demand for tomato-growing (Van Dijk, 2009). The 2008 oil and gas prices resulted in strong interest in geothermal projects in the Netherlands.

Since transport of heat has limitations, geothermal heat can only be used where there is demand in the vicinity of the resource. There are several examples of the profitable use of surplus geothermal heat enhancing local economic development. In Croatia, the development of a CHP plant using the geothermal resources of the Pannonian Basin has been welcomed by the community, since it enables additional developments aimed at stimulating the local economy. A new business and tourist facility is planned, with outdoor and indoor pools, greenhouses and fish farms. The project is expected to employ 265 people, 15 of them at the power plant.

Geothermal district cooling is poorly developed but could provide a summer use for geothermal district heating systems. Geothermal heat above 70°C can produce chilled water in sorption chillers that can be piped to consumers via the same circuit used for heating. Alternative devices such as fan coils and ceiling coolers can also be used. Sorption chillers have recently become available that can be driven by temperatures as low as 60°C, enabling geothermal heat drive compression chilling machines in place of electricity.

Enablers for development and use of geothermal energy

Whether a geothermal resource is used to produce electricity and/or heat, several disciplines and techniques will always be needed, notably resource assessment and means of accessing and engineering the resource.

Resource assessment

Geothermal resources are found deep beneath the surface so exploration is needed to locate and assess them. Exploration consists of estimating underground temperature, permeability and the presence of fluid, as well as the lateral extent, depth and thickness of the resource, by using geosciences methods and by drilling exploration wells. The local state of stress must be assessed, too, particularly in the case of EGS. Exploration drilling involves high financial risks as it is expensive and the results are mainly unknown in advance. Wells in sedimentary, hydrothermal reservoirs, where geological formations resemble those exploited for oil and gas, can be drilled using similar methods. In contrast, economic drilling of low-cost exploration-only boreholes and drilling into deep, hard rock formations pose technical challenges requiring new and innovative solutions. Improvement of geophysical data inventories and geoscience exploration methods, as well as innovative geothermal resource assessment tools, will reduce the exploration risk and thus lower a barrier for investment in geothermal energy.

Accessing and engineering the resource

As well as aiding resource assessment, competitive drilling technology will make it easier to access and engineer geothermal resources. Reservoir stimulation technology is also extremely important, both for hydrothermal reservoirs, where the connection of a production well to the reservoir fluids requires improvement, and for creating EGS reservoirs in hot rock resources. Stimulation techniques to boost the conductivity and connectivity of hot rock resources will make it possible to access larger volumes of rock. Stimulation can be hydraulic, by injecting fluids, or chemical, by injecting acids or other substances that will dissolve the rock or the material filling the fractures. Both hydraulic fracturing and chemical stimulation techniques are similarly deployed in unconventional oil and gas reservoir developments. Hydraulic stimulation creates permeability, releasing seismic energy. In hydraulic fracturing, as in any sort of fluid injection or re-injection that raises underground fluid pressure, there is a risk of inducing micro-seismic events intense enough to be felt on the surface. Induced seismicity effects also depend on the existing stress field.

Economics today

Where high-temperature hydrothermal resources are available, in many cases geothermal electricity is competitive with newly built conventional power plants. Binary plants can also achieve reasonable and competitive costs in several cases, but costs vary considerably depending on the size of the plant, the temperature level of the resource and the geographic location. EGS costs cannot yet be assessed accurately because the limited experience available has only been derived from pilot plants where economics are relatively unimportant. Geothermal heat may be competitive for district heating where a resource with sufficiently high temperatures is available and an adaptable district heating system is in place. Geothermal heat may also be competitive in applications where there is a high, continuous, heat demand and where there is no need for a large distribution system, *e.g.* in greenhouses. Although geothermal electricity and heat can be competitive under certain conditions, it will be necessary to reduce the levelised cost of energy (LCOE) of less conventional geothermal technology.

Investment costs

Geothermal electricity development costs vary considerably as they depend on a wide range of conditions, including resource temperature and pressure, reservoir depth and permeability, fluid chemistry, location, drilling market, size of development, number and type of plants (dry steam, flash, binary or hybrid), and whether the project is a greenfield site or expansion of an existing plant. Development costs are also strongly affected by the prices of commodities such as oil, steel and cement. In 2008, the capital costs of a greenfield geothermal electricity development ranged from USD 2 000/kW_e to USD 4 000/kW_e for flash plant developments and USD 2 400/kW_e to USD 5 900/kW_e for binary developments (IEA, 2010a). The highest investment costs for binary plants can be found in Europe in small binary developments (of a few MW_e) used in conjunction with low- to medium-temperature resources. It is not yet possible to assess reliable investment data for EGS because it is still at the experimental stage.

Investments costs for district heating range from USD 570/kW_t to USD 1 570/kW_t (IPCC, forthcoming). For use of geothermal heat in greenhouses, investment costs range from USD 500/kW_t to USD 1 000/kW_t (ibid.).

Operation and maintenance costs

Operation and maintenance (O&M) costs in geothermal electricity plants are limited, as geothermal plants require no fuel. Typical O&M costs depend on location and size of the facility, type and number of plants, and use of remote control; they range from USD 9/MWh_e (large flash, binary in New Zealand) to USD 25/MWh_e (small binary in USA), excluding well replacement drilling costs (IEA, 2010). When make-up wells are considered to be part of O&M costs, which is usual in the geothermal electric industry, O&M costs are estimated at USD 19/MWh_e to USD 24 /MWh_e as a worldwide average (IPCC, forthcoming), although they can be as low as USD 10/MWh_e to USD 14 /MWh_e in New Zealand (Barnett and Quinlivan, 2009).

Production costs

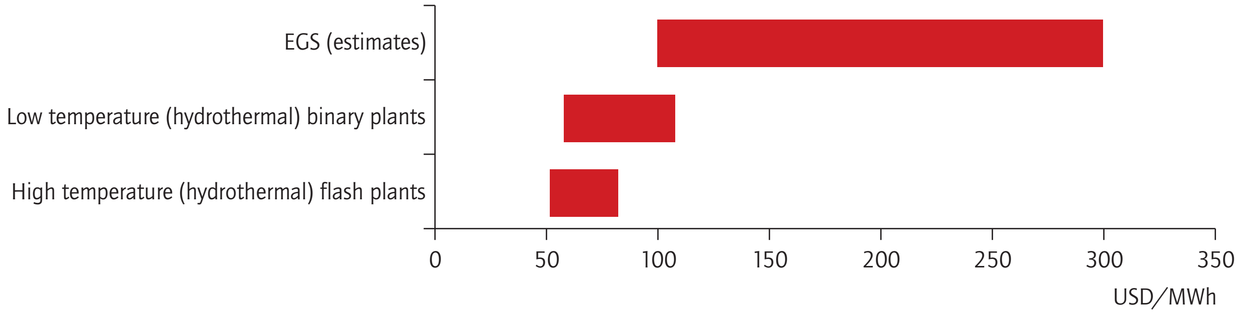
Levelised generation costs of geothermal power plants vary widely. On average, production costs for hydrothermal high temperature flash plants have been calculated to range from USD 50/MWh_e to USD 80/MWh_e. Production costs of hydrothermal binary plants vary on average from USD 60/MWh_e to USD 110/MWh_e (assumptions behind cost calculations are included in Appendix I). A recent case of a 30 MW binary development (United States) showed estimated levelised generation costs of USD 72/MWh_e with a 15-year debt and 6.5% interest rate (IEA, 2010). New plant generation costs in some countries (*e.g.* New Zealand) are highly competitive (even without subsidies) at USD 50/MWh_e to USD 70/MWh_e for known high-temperature resources. Some binary plants have higher upper limits: levelised costs for new greenfield plants can be as high as USD 120/MWh_e in the United States and USD 200/MWh_e in Europe, for small plants and lower-temperature resources. Estimated EGS development production costs range from USD 100/MWh_e (for a 300°C resource at 4 km depth) to USD 190/MWh_e (150°C resource at 5 km) in the United States, while European estimates are USD 250/MWh_e to USD 300/MWh_e (IEA, 2010a).

Box 4: Cost of financing geothermal plants

The levelised cost of generating geothermal energy depends on the origin of the resources invested and the way they are secured, as well as the amount of the initial capital investment. In the case of geothermal development, in some countries such as the United States, debt lenders (typically charging interest rates from 6% to 8%) usually require 25% of the resource capacity to be proven before lending money, so the early phases of the project, which have a higher risk of failure, often have to be financed by equity at higher interest rates (Hance, 2005). The average capital structure of geothermal power projects is composed of 55%-70% debt and 45%-30% equity. Large utilities building their own plants, either with their own available balance sheet or with cash flows, have a different cost structure from other investors when combining equity and loans to finance plants. Different financing schemes can have significant consequences on the costs of generating electricity and the expected rates of return on investment. Costs can be reduced by the availability of a long-term energy supply contract from a creditworthy off taker.

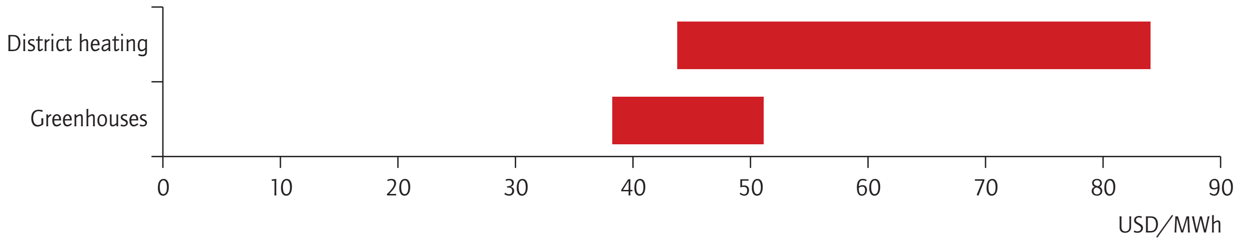
Use of geothermal energy for district space heating can have a wide range of costs depending on the specific use, the temperature of the resource and O&M and labour costs. District space heating costs range from USD 45/MWh_t to USD 85/MWh_t. Costs of heating greenhouses vary between USD 40/MWh_t and USD 50/MWh_t (assumptions behind cost calculations are included in Appendix I).

Figure 6: Production costs of geothermal electricity (USD/MWh_e)



Note: Assumptions calculation included in Appendix I.
Source for binary plants and flash plants: IEA analysis.
Sources for EGS estimates: MIT, 2006; and Huenges and Frick, 2010.

Figure 7: Production costs of geothermal heat use (USD/MWh_t)



Note: Assumptions calculation included in Appendix I.
Source: IEA analysis.

Vision for deployment and CO_2 abatement

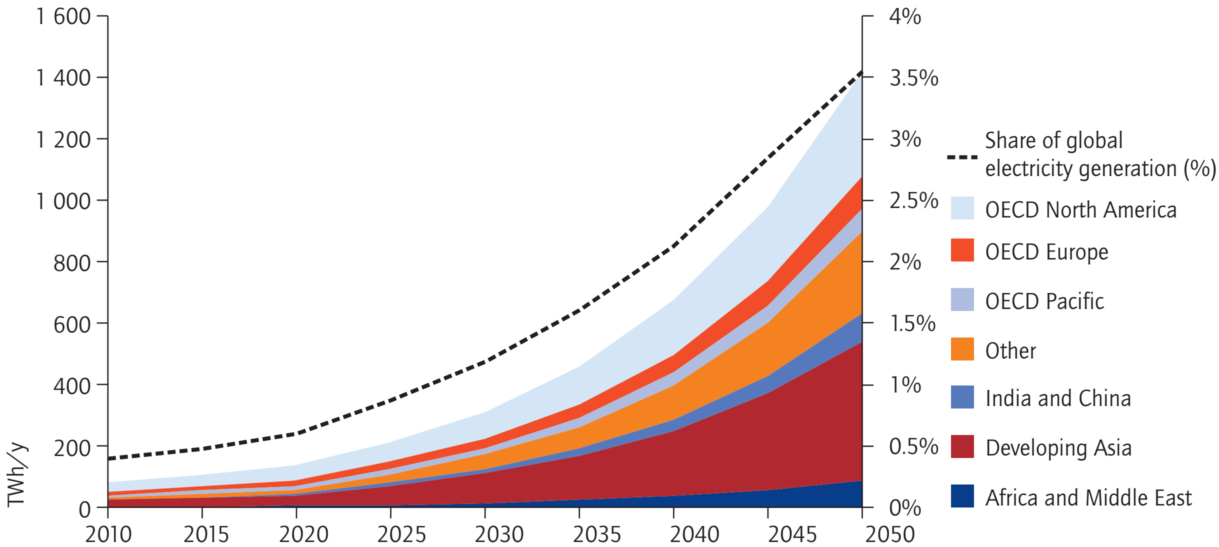
Geothermal deployment to 2050

Electricity

For this roadmap, the *ETP 2010* BLUE Map Hi-REN scenario was chosen as the basis for the projection of geothermal power by 2050 (Box 5). This scenario assumes that renewable energy sources will provide 75% of global electricity production in 2050 and foresees geothermal electricity producing 1 400 TWh annually by 2050 (Figure 8). This will amount to around 3.5% of global electricity production by that time on the basis of a projected 37 500 TWh/yr in 2050 in the ETP2010 BLUE Hi REN scenario (IEA, 2010b). Conventional high-temperature resources as well as deep aquifers with low- and medium-temperature resources are expected to play an important role in geothermal development. Advanced hot rock geothermal technologies are assumed to become commercially viable soon after 2030.

There is great potential for geothermal power in developing countries in Asia, where abundant high-temperature hydrothermal resources have yet to be exploited. OECD North America also shows considerable growth expectations, not only from high-temperature hydrothermal resources in the western United States but also from development of EGS. Geothermal development in OECD Europe is expected to come from a combination of high-temperature hydrothermal, deep aquifers with low- and medium-temperature resources and EGS.

Figure 8: Roadmap vision of geothermal power production by region (TWh/y)



Box 5: *Energy Technology Perspectives* (*ETP*) *2010*

The IEA publication *Energy Technology Perspectives* (*ETP*) *2010* puts geothermal energy in competition with all other zero- or low-carbon technologies to delineate the economically optimal energy mix leading to specified global energy-related CO_2 levels by 2050 (IEA, 2010). The ETP2010 BLUE Map scenario describes how the energy economy may be transformed by 2050 to achieve the global goal of reducing annual CO_2 emissions to half that of 2005 levels. The Energy Technology Perspectives 2010 also show a variant of the BLUE scenario that is presented as the "BLUE Hi-REN" ("high renewables") scenario. This scenario assumes renewables to provide 75% of global electricity production in 2050. Under the BLUE Hi-REN scenario, geothermal electricity would globally produce 1 400 TWh annually by 2050, from a capacity of 200 GW_e.

Box 5: *Energy Technology Perspectives (ETP) 2010* (continued)

The IEA *Energy Technology Perspectives* (*ETP*) uses a bottom-up MARKAL model with cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. ETP global 15-region model permits the analysis of fuel and technology choices throughout the energy system. Its detailed representation of technology options includes about 1 000 individual technologies. The ETP scenario studies result from development of the model over several years and use in many analyses of the global energy sector (*e.g.* IEA, 2005; IEA, 2006; IEA, 2008). The ETP model was supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

A significant proportion of high-temperature (on-shore) hydrothermal resources are expected to have been developed by 2050 because their affordable power prices and base-load electricity supply will become increasingly attractive as wholesale electricity prices rise (see Figure 12).

Low- and medium-temperature hydrothermal resources (typically found in deep aquifers) are expected to be exploited in power plants in warm climate countries and in combined heat and power plants in countries with high heat demands. Strong development of binary CHP plants has already been shown in recent years in Germany. The sale of heat from CHP development (*e.g.* for district heating) can increase the economic viability of lower-temperature resources.

In this roadmap's vision, advanced hot rock technologies such as EGS are expected to become commercially viable after 2030. Once technical and economic challenges for EGS are overcome, or other methods of exploiting hot rock resources become available (*e.g.* without fracturing the underground bedrock), geothermal deployment could be pursued wherever rock temperatures and other underground properties allow the economic sale of energy. This would mean that advanced geothermal systems could be deployed where demand for electricity and heat exist.

This roadmap's vision for geothermal electricity foresees 200 GW_e of installed capacity by 2050, including 100 GW_e hydrothermal electricity capacity and 100 GW_e from EGS (Figure 9). EGS is expected to mostly use binary power generation technology.

Figure 9: Growth of geothermal power capacities by technology (GW)

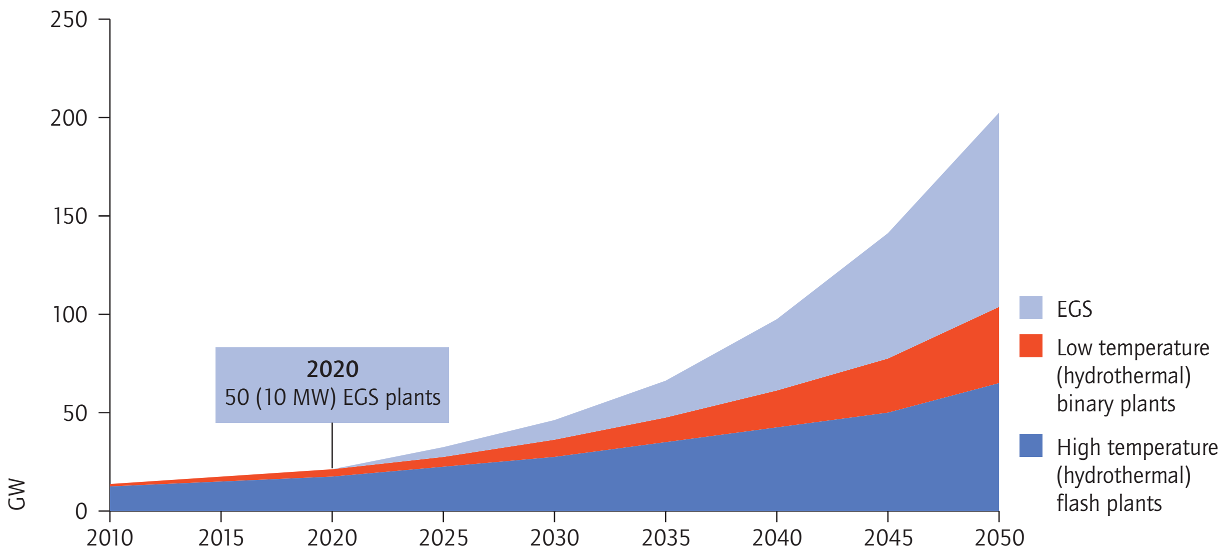
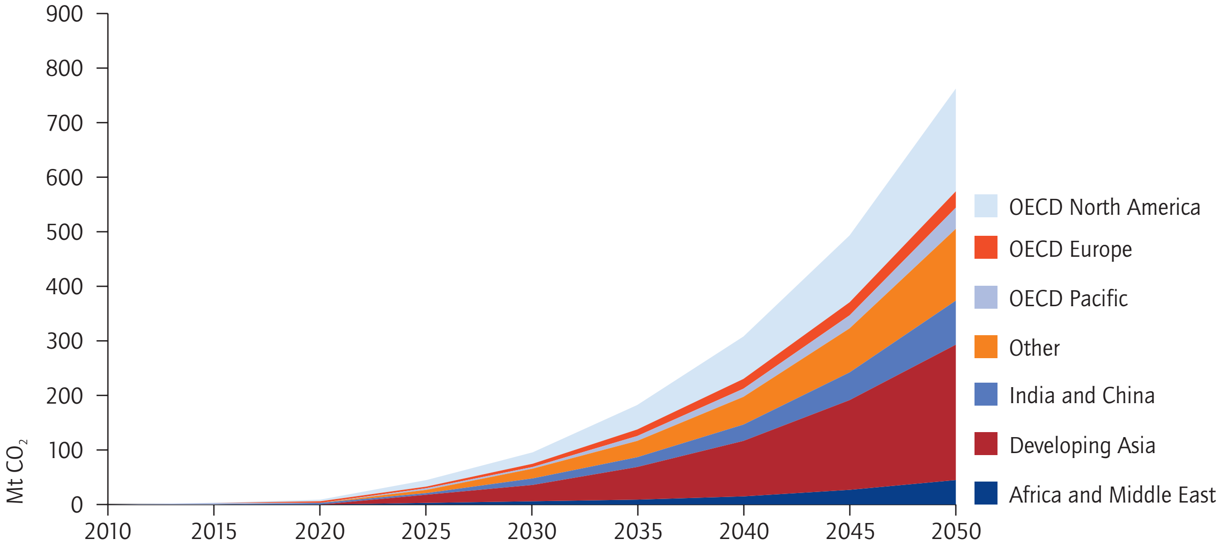


Figure 10: CO_2 emission reductions from geothermal electricity by 2050



In addition to the 10 EGS plants currently under development, at least 50 more with an average capacity of 10 MW_e will be needed over the next 10 years to achieve the deployment levels envisaged in this roadmap and shown in Figure 9. EGS plant capacities are expected to increase: while the pilot plant in Soultz-sous-Forêts is producing power from a 1.5 MW capacity, plants under development aim for capacities from 3 MW to 10 MW_e in the next decade. In course of time, plants are expected to increase capacities to 50 MW_e and eventually more than 200 MW_e by stacking modules in series and parallel.

The 1 400 TWh of geothermal electricity generated by 2050 is expected to avoid around 760 megatonnes (Mt) of CO_2 emissions per year worldwide according to the *ETP 2010* (IEA, 2010b) (Figure 10). The reductions are relative to the *ETP 2010* Baseline Scenario in the corresponding year, and have been estimated by assuming that the additional geothermal generation in the BLUE Map Hi-REN Scenario replaces the average fossil generation mix in the Baseline Scenario. In the *ETP 2010* calculation of CO_2 emission reductions, all new geothermal plants are assumed to be CO_2-free (Box 6).

Box 6: CO_2 emission reductions from geothermal electricity

Geothermal power plants can emit greenhouse gases (GHG), but these result not from combustion but from natural CO_2 fluxes. For this reason, some say these emissions cannot be compared with CO_2 emissions from combustion of fossil fuels. During operation, measured direct CO_2 emissions from partially open-cycle power or heating plants in high-temperature hydrothermal fields vary between 0 and 740 g/kWh_e with a worldwide average of 120 g/kWh_e. By comparison, CO_2 emissions of lignite/brown coal plants amount to 940 g/kWh_e, whereas gas plants account for 370 g/kWh_e (IEA, 2010f). In low-temperature applications, emissions reach a maximum of 1 g/kWh_e (Bertani and Thain, 2002; Bloomfield *et al*., 2003).

In closed-loop power plants, when geothermal fluid is completely re-injected into the ground without loss of vapour or gas to the atmosphere, emissions are nil. Most new geothermal plants, including EGS plants, are now designed as closed-loop systems and thus are expected to have zero direct emissions during operation. In heating applications, emissions during operation are negligible.

Geothermal heat use

Geothermal heat use may be most relevant in colder countries, but in warmer climates geothermal heat can be made useful in agricultural and industrial applications, and for space cooling using heat in excess of 60°C as the driving energy for sorption chillers.

Recent rapid increases in the numbers of geothermal heat-only plants and in geothermal CHP binary plants in northern Europe confirm that interest in the direct use of geothermal heat is growing. Several East European countries face the need to renovate ageing district heating systems, while realising that they are located above or close to deep geothermal aquifers such as the Pannonian Basin. Even tropical countries such as the Philippines and Indonesia are starting to become aware of the potential benefits of geothermal heat for agricultural applications.

Projections for geothermal heat use are related to the development of advanced technologies, which will benefit from the combined use of heat and power as this can increase economic viability of more expensive technology.

Figure 11 illustrates the vision of the growth, on a regional basis, of geothermal heat use until 2050,[7] when the global sum of annual direct use amounts to 5.8 EJ (about 1 600 TWh thermal energy).[8] The figures for deployment of geothermal heat use are based on the IPCC SSREN projections for geothermal heat, removing contributions from ground-source heat pumps and adding full use of the potential of combined heat and power generation via EGS technology[9]. This scenario assumes that hot rock technology becomes commercially viable soon after 2030. Under this assumed condition, the utilisation of heat from deep rock formations should theoretically become possible wherever rock temperatures and the properties of the underground allow the economic sale of energy.

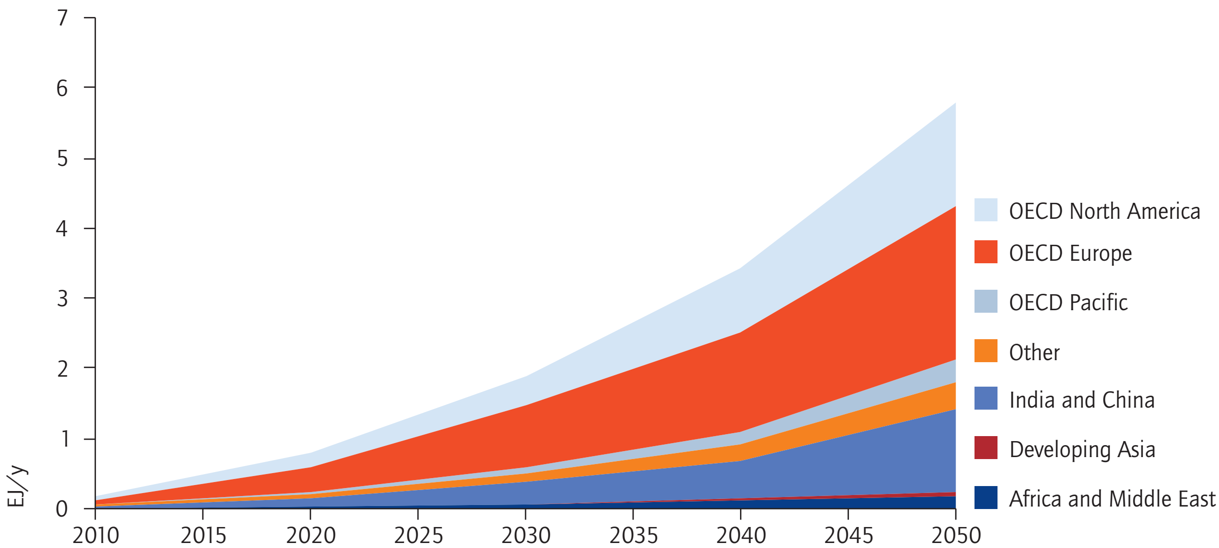
The largest potential for geothermal heat can be found in regions with high heat demand: Europe, China and North America.

7. This roadmap's vision excludes contributions from ground source heat pumps. A projection of heat produced by ground source heat pumps can be found in Annex III.

8. In 2008, worldwide final energy for heat was 160 EJ (IEA, 2010e). In the IEA *Energy Technology Perspectives 2010* BLUE Map scenario, final energy for heat is projected to be 150 EJ by 2050, which shows that in this high-efficiency and high-renewables scenario, heat demand decreases slightly (IEA, 2010b).

9. The geothermal heat scenario is an IEA estimate based on IPCC SRREN projection, the *ETP 2010* Hi-Ren scenario and the EREC 2010 scenario (IPCC, forthcoming), (IEA, 2010b), (EREC, 2010)

Figure 11: Roadmap vision of direct use of geothermal heat by region, excluding ground source heat pumps (EJ/y)



Economic perspectives and cost reduction

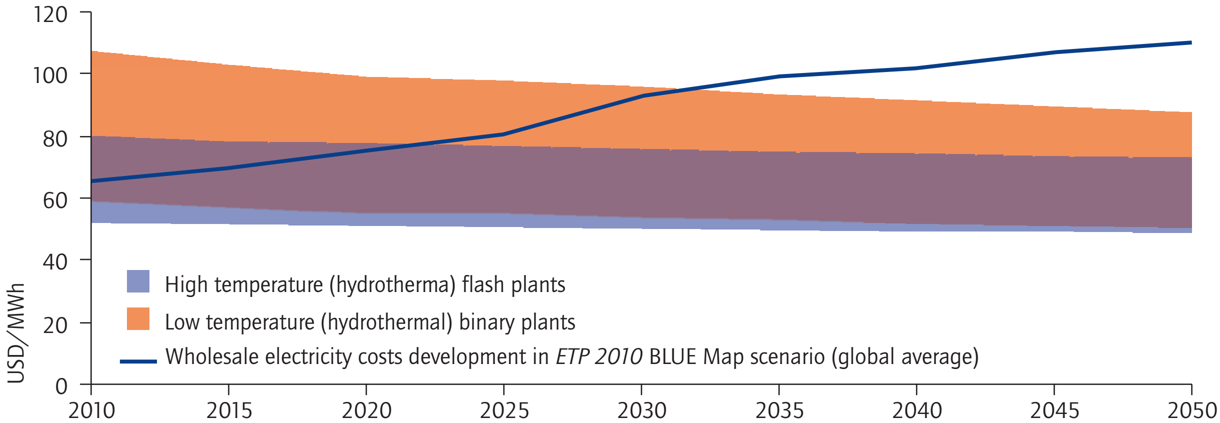
The production costs of geothermal energy vary considerably, as explained in the previous section. Flash plants in high-temperature resources may be considered proven technology with an average learning rate of 5% .[10] Costs of electricity production in flash plants, in many situations already competitive, are estimated to continue to fall at a moderate rate towards 2050 (Figure 12). Binary (hydrothermal) plants, working with lower-temperature resources, are also considered to be a relatively mature technology. For binary plants, which currently have small capacities, costs will decrease to competitive levels as capacities increase.

With wholesale electricity prices expected to rise over time, hydrothermal flash plants are expected to be fully competitive between 2020 and 2030. Hydrothermal binary plants should be fully competitive after 2030.

10. A 5% learning rate means a 5% decrease in investment per kW when cumulative installed capacities double. The 5% learning rate assumption was taken from the *Energy Technology Perspectives 2010* (IEA, 2010).

Cost projections could not be calculated for EGS because actual investment costs were lacking and most existing projects are still pilot-scale with a high component of R&D funding, particularly in the drilling and stimulation phases. The same applies to advanced hydrothermal technologies like co-produced hot water from oil and gas wells, offshore geothermal, geo-pressured and super-critical resource development. For geothermal heat technologies, cost projections could not be calculated because information on deployment figures for each technology was lacking.

Figure 12: Range of reduction of average levelised costs of electricity production in hydrothermal flash plants and binary plants



Note: Assumptions: interest rate 10%, technical lifetime 35 years, O&M costs 2.5%
Source: IEA analysis.

Technology development: actions and milestones

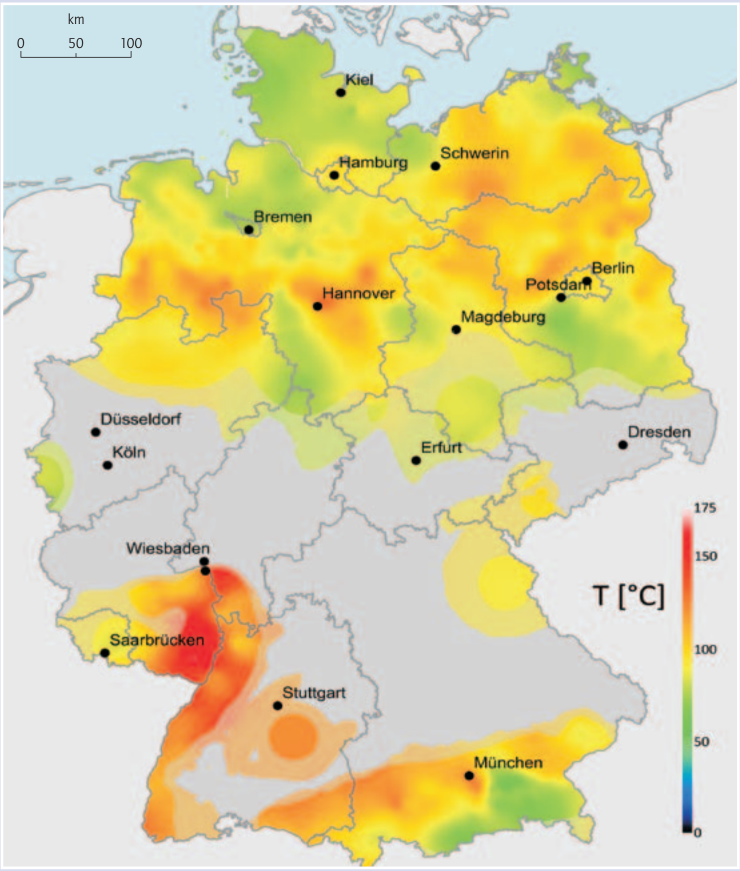
Enabling processes for geothermal energy

Geothermal resource assessment

This roadmap recommends the following actions:	*Milestone timeline*	*Stakeholders*
Compile and combine existing geological databases, and expand geological datasets to develop a publicly accessible database of geothermal resources.	2011-15	Governments, geothermal industry, hydrocarbon industry and research institutes.
Develop an integrated approach for identification of hot rock and advanced hydrothermal resources, and assessment of their geothermal potential.	2011-20	Research institutes and geothermal industry.
Develop geothermal tools and sub-surface models for identifying suitable hot rock and hidden hydrothermal sites.	2015-25	Research institutes, hydrocarbon industry and geothermal industry.

Box 7: Public geothermal information systems

Figure 13: Underground temperature in Germany at 2 500 m below sea level



Source: Geotis.

The German Geothermal Information System is a public, Internet-based atlas that provides information and data compilations on deep aquifers relevant for geothermal exploitation in Germany. Based on hydrocarbon exploration data, hydraulic data and geophysical recordings, as well as geological maps and seismic surveys, the system helps to identify geothermal potentials by visualising temperature, hydraulic properties and depth levels of relevant stratigraphic units. GeotIS cannot replace local feasibility studies, but serves as a useful tool to minimise exploration risk and improve the quality of geothermal project planning (GeotIS, www.geotis.de).

Box 7: Public geothermal information systems (continued)

The Dutch public information system includes high-resolution 3D geological models covering the complete onshore area of the Netherlands, outlining key geothermal reservoirs and allowing assessment of relevant parameters and underlying uncertainties. State-of-the-art 3D modelling techniques have been used to obtain reservoir structures, flow properties and temperatures, using constraints from over 1 000 deep wells, and detailed 3D and 2D seismic sub-surface mapping. Users can obtain key reservoir parameters and underlying uncertainties at any location and for any reservoir (thermoGIS, www.thermogis.nl).

In the framework of the Joint Programme on Geothermal Energy of the European Energy Research Alliance (EERA), a global geographical information system has been developed for assessing the geothermal energy potential from sedimentary aquifers for low enthalpy applications (ca. 40°C to 150°C). The tool is intended to provide a global overview for the direct use heat potential and should not be used for a local potential assessment. The maps will continuously be updated whenever more detailed data become available (www.thermogis.nl/worldaquifer).

Geological databases already exist for several parts of the world. Combining these, extending them geographically, and reinterpreting, recompiling and standardising them would enable the creation of a publicly accessible, globally relevant database for use in assessing, accessing and exploiting geothermal resources. Efficient and effective performance of these tasks requires co-operation among geothermal industry groupings, national authorities and research institutes.

Industry players and research institutes are now working towards an integrated approach for a comprehensive characterisation of hot rock resources in a variety of geological settings. R&D will need to focus on understanding better how fractures open and propagate in different stress regimes and rock types, in order to be able to better assess the hot rock potential. Similarly, a common approach in identification of advanced hydrothermal resources will help assessing its potential.

R&D is required to enable exploration and assessment of hidden hydrothermal geothermal systems and hot rock resources. Rapid reconnaissance geothermal tools will be essential to identify new prospects, especially those with no surface features like hot springs. Verification is needed as to whether airborne-based hyper-spectral, thermal infra-red, magnetic and electromagnetic sensor tools can provide data inexpensively over large areas. Other tools might include ground-based verification, soil sampling and geophysical surveys (magneto-telluric, resistivity, gravity, seismic and/or heat flow measurements). Exploration-only drilling technology is vital to enable EGS, because the *in situ* stress field can only be measured in boreholes, but it needs to become much cheaper in order to be affordable.

Accessing and engineering the resource

This roadmap recommends the following actions:	*Milestones*	*Stakeholder*
Develop cheaper drilling technologies for exploration, resource assessment, and development and exploitation of reservoirs and explore advanced drilling approaches.	2011-25	Drilling industry, research institutes, hydrocarbon industry and geothermal industry.
Improve hard rock and high-temperature, high-pressure drilling technology.	2011-20	Drilling industry, research institutes, hydrocarbon industry and geothermal industry.
Improve downhole instrumentation and well monitoring.	2011-20	Drilling industry, research institutes, hydrocarbon industry and geothermal industry.

Drilling costs constitute a substantial portion of the total cost of geothermal energy. Thus, the performance of the whole geothermal industry stands to improve – and a larger portion of the geothermal resource would become economically accessible – if drilling costs could be dramatically reduced and supplemented by improved drilling methods and novel exploration techniques.

Evolutionary improvements of conventional drilling, such as drill bits carefully matched to the rock type, innovative casing methods and better cementing techniques for high temperatures, can improve drilling economics. Novel or even revolutionary drilling concepts are expected to become practicable only in the longer term (after 2025). New drilling technology for prospective investigation includes millimeter wave deep drilling; hydrothermal spallation drilling (flame and/or superheated steam heat sources); robotic, ultra-deep, high-temperature drilling; thermal, particle-assisted abrasives; and chemically assisted drilling. Some new drilling technology may be more expensive but more efficient, thus resulting in reduced drilling costs per installed capacity. Innovations can save time during rig manipulation, which can also reduce costs.

Development of new drilling technology requires collaboration between industry and research institutes, as was the case when the Seismic Prediction While Drilling tool was developed in Germany (Wenke *et al.*, 2010). Some solutions to geothermal drilling challenges may come from the much larger oil and gas industry, which uses similar technology, but the geothermal industry will need to develop services and equipment that the oil and gas sector may not require. Multilateral wells and batch-drilling of wells may substantially reduce costs, along with optimisation of the engineering, design and number of wells in geothermal projects. The oil and gas industry has demonstrated that standardisation and simplification can lead to a 40% reduction in drilling cost between the first and the fifth or sixth well for a project.

Hard rock drilling poses a challenge that needs to be met to develop hot rock resources. Skilled adaptations of oil and gas drilling materials and methods to hard rock with a focus on rock bits have been shown to save rig time and mitigate drilling risks but difficulties still exist, *e.g.* resistance to vibrations in the drill string. High-temperature, high-pressure drilling is of specific interest in locations (such as in Iceland) with natural supercritical hydrous fluids at drillable depths. Producing supercritical fluids will require improved equipment to allow wells to be drilled at temperatures of 450°C to 600°C (Box 8).

Box 8: Exploration of supercritical fluids

Today, geothermal resources with temperatures up to 350°C can be reliably exploited. Technological progress suggests that it could be possible to exploit very high enthalpy systems with temperatures higher than 375°C. At these temperatures and fluid pressures in excess of 22 MPa (about 2 km depth), water is in a supercritical state, which allows at least 10 times more energy to be produced than from current systems. This objective is being investigated in the framework of the Iceland Deep Drilling Project (IDDP).

In exploring and assessing geothermal fields, it is often a considerable challenge to collect reliable reservoir and fluid data in the hot and corrosive environments frequently encountered. Downhole communication technologies should allow for real-time downhole data while drilling in order to continuously assess bit performance, sudden pressure changes and temperature spikes so that problems can be mitigated or avoided. Such downhole instruments exist and are relatively mature in the hydrocarbon industry. However, the combinations of high pressures, high temperatures and aggressive chemical environments often encountered in geothermal energy exploration and exploitation can cause problems for electronic components, instrument bodies and cable materials. Development of improved sensors and electronics capable of operating at high temperatures in downhole tools is required, as well as peripheral equipment such as cables that can resist high temperatures.

Geothermal heat use

This roadmap recommends the following actions:	*Milestones*	*Stakeholder*
Increase efficiency and performance of combined heat and power (CHP) production by improving components such as pumps, heat exchangers, re-injection technology, scaling prevention, peaking/back up unit and storage tank. Optimise balance between heat and power load in geothermal CHP.	2011-15	District heat industry, research institutes and geothermal industry.
Explore expansion of possibilities for geothermal heat use by means of cascade use, use in space cooling, in new (industrial) applications and hot rock CHP.	2015-25	District heat industry, research institutes and geothermal industry.

Geothermal heat use will expand as resource assessment improves. New CHP plants should move closer to economic viability with evolutionary improvements of components, re-injection technology, scaling and corrosion prevention, peaking/back-up units and storage tanks. In geothermal CHP, the balance between heat and power load needs more attention, *e.g.* by looking at the effectiveness of alternative uses of heat in summer, such as in absorption chillers.

Experiences with integrated or cascaded systems are needed in pilot and demonstration plants fed by geothermal heat, particularly with combinations of heat utilisations in series, such as using the waste heat of a district heating network for agricultural crop drying and then for snow melting. Economic benefits can be achieved by combining heating and cooling, as the resulting load factor is higher than with heating alone, and the unit energy costs are less. Other innovative geothermal heat applications that need to be demonstrated in pilot projects are sea water desalination plants and preheating for high-temperature process heat. Moreover, the feasibility of creating and building a combined heat and power EGS plant needs to be demonstrated, as this will also open up a promising market for replacing fossil-fuelled, district-heating boiler plants with geothermal heating plants.

Advanced geothermal technologies: EGS

This roadmap recommends the following actions:	*Milestones*	*Stakeholder*
Develop EGS pilot plants in different geological environments including by cross-fertilisation with hydrothermal development.	2011-20	Geothermal industry, governments and research institutes.
Develop standardised chemical, thermal and hydraulic stimulation techniques, and new decision tools for optimal reservoir modelling and to enhance EGS production.	2011-30	Geothermal industry, research institutes.
Improve management of health, safety and environmental (HSE) issues, including risk associated with induced seismicity.	2011-20	Geothermal industry, research institutes.
Realise long-term availability of the resource, monitoring and reservoir management in EGS.	2015-25	Geothermal industry, research institutes.
Scale up EGS plants to 50 MW and then to 200+ MW by stacking modules in series and/or parallel.	Starting 2025	Geothermal industry.

New and innovative techniques for exploration, stimulation and exploitation are needed to make EGS technology commercially viable. The key technical and economic challenge for EGS is to achieve efficient and reliable stimulation of multiple reservoirs. This will require well-distributed heat-exchange surfaces that are large enough to attain the volumes needed for long-term production, with low flow impedance, limited short-circuiting fractures and manageable water loss. One prerequisite for dissemination of EGS technology is proof that the underground heat exchanger can be successfully engineered under all possible site conditions.

EGS pilot plants are needed in different geological environments. To realise the growth of EGS shown in Figure 9, some 50 EGS plants, with an average capacity of 10 MW, will have to be planned by the year 2020, in addition to the 10 EGS pilot plants currently planned or in operation. Effort should also be expanded to apply EGS techniques to hydrothermal fields. One such concept is to extend existing hydrothermal fields by drilling wells on their boundaries, in appropriate directions with reference to the local stress field, and stimulate them to connect the field to the main hydrothermal reservoir. This would extend the life of a hydrothermal field and deliver more power. Cross-fertilisation between EGS and tight oil and gas fields is also worth exploring: the technology is very similar and the hydrocarbon industry is aware of the potential to move EGS much faster and more successfully.

EGS reservoir engineering requires the ability to routinely create EGS reservoirs with sufficient permeability, fracture orientations and spacing to allow long-term energy extraction. This implies developing improved means of downhole zonal isolation for fracture stimulation and production, including packer, sliding sleeve and multilateral technologies. New tools are needed to isolate specific zones in a hot borehole for both fracture creation and short-circuit repair, which would enable multiple fracture zones from a single borehole, enhance water circulation rates, and reduce the specific cost of the system creation and activation. Stimulation procedures need to be refined to significantly enhance hydraulic productivity, while reducing the risk associated with induced seismicity. New visualisation and measurement methodologies (*e.g.* imaging of borehole, permeability tomography, tracer technology, coiled tubing technology) should become available for reservoir characterisation.

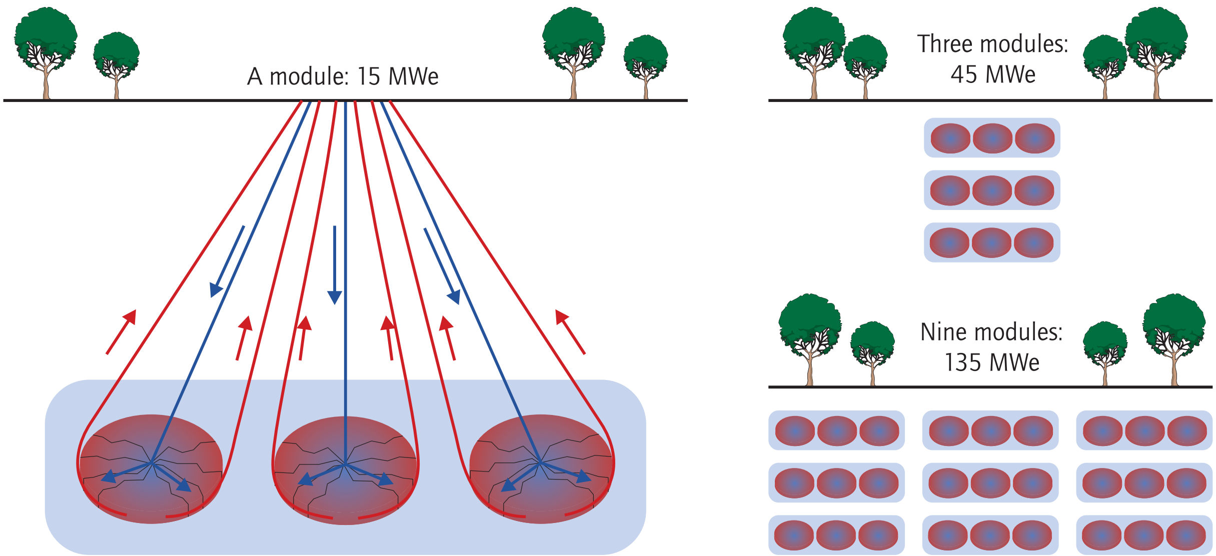
Developing EGS requires keeping health, safety and environmental (HSE) risks as low as reasonably practicable. The impact of felt induced seismicity or micro-seismicity at EGS sites in France, Germany and Switzerland has created public concern. Because no EGS project has been in production for longer than three years, knowledge is scarce of how they will behave seismically over the long term. More knowledge about expected micro-seismic activity should result from the first experiences with pilot plant operation.

To mitigate risks related to induced seismicity, strategies are needed to set requirements for seismic monitoring and for prolonged field operation. Technologies for imaging fluid pathways induced by hydraulic stimulation treatments would constitute a major improvement of the EGS concept. Geochemical research is needed to better understand the effects and amounts of sub-surface precipitation and dissolution of injected fluids during production and injection.

Careful monitoring and modelling, as well as energy-efficient utilisation, are essential to sustainable geothermal reservoir management. Innovative monitoring techniques (such as interactive calibrated simulations of EGS reservoir behaviour) will be needed to reliably forecast future pressure, temperature and flow trends and reservoir life. Modelling of the maximum energy production of EGS plants needs to be developed to ensure longevity of the resource. More knowledge is still needed in effects of cooling down of the host rock and preventing or repairing short-circuiting of flow paths in connected fracture systems, which can reduce the lifetime of reservoirs.

To ensure that EGS becomes a worldwide application with reasonable power output, the technology will have to be scaled up in stages from the 5 MW_e to 15 MW_e capacities of pilot plants to anything from 50 MW_e to more than 200 MW_e soon after 2025 (Figure 14). Such capacities will accelerate deployment by attracting the interest of the hydrocarbon industry. It may also be possible to scale up existing EGS pilot plants by stacking modules in series and parallel, to produce sensible power from a single site.

Figure 14: Conceptual model of an industrial EGS plant



Source: EGS Energy.

Advanced geothermal technologies: other

This roadmap recommends the following actions:	*Milestones*	*Stakeholder*
Explore feasibility of alternative ways to exploit hot rock resources.	2011-25	Research institutes, national governments and geothermal industry.
Explore feasibility of alternative technologies to exploit hydrothermal resources such as supercritical fluids and co-produced hot water from gas and oil wells.	2011-20	Research institutes, national governments and geothermal industry and hydrocarbon industry.
Explore feasibility of alternative technologies to exploit off-shore hydrothermal resources.	2020-40	Research institutes, national governments and geothermal industry

Other conceptual approaches to engineering hot rock reservoirs merit attention. Alternative approaches aim to create connectivity between water inlet and water outlet, for example by drilling a sub-surface heat exchanger made of underground tubes or by drilling a long (7 km to 10 km) vertical tunnel of large diameter that contains both water inlet and water outlet. Theoretical studies are needed to determine the economic and technical feasibility of such approaches, including whether they can achieve an adequate heat exchange potential.

Hot water from gas and oil wells is another source of hydrothermal fluid. Normally regarded as an unwanted waste product, under favourable circumstances this heat could be turned into an asset. Recently more attention and some governmental seed money have been dedicated to this type of geothermal development. Geothermal exploitation has already raised interest from the hydrocarbon industry in a few cases where it has supported remote field operations as well as pre-heating of unconventional, very viscous, petroleum deposits. Exploration of the feasibility of exploiting geothermal resources with temperatures higher than 375°C, so called super-critical fluids, should be continued.

The potential of unconventional hydrothermal resources, such as offshore geothermal vents or even magma, needs to be assessed. The necessary technology for offshore geothermal has not yet been developed, but it may be possible to exploit ocean-floor geothermal vents directly without drilling, using an encapsulated submarine binary plant to produce power. The main challenges for offshore geothermal development include the distance to shore, water depth, grid connection and disturbance of marine life around hydrothermal vents. Technology developed to exploit offshore wind and ocean energy may help meet these challenges.

Policy framework: actions and milestones

Regulatory framework and support incentives

This roadmap recommends the following actions:	Milestones	Stakeholder
Set medium-term targets for (nearly) mature geothermal technologies and long-term targets for advanced geothermal technologies to produce electricity and heat. These targets should be based on exploration of the potential of all types of geothermal resources and be included in an overall policy framework.	2011-15	Government
Introduce differentiated economic incentives, such as feed-in tariffs or renewable portfolio standards, by means of a transparent and predictable regulatory framework to bridge their respective competitive gaps.	Start 2011, phase out depending on development of competitiveness.	Government
Introduce (innovative) economic incentives for geothermal heat use.	Start 2011, phase out depending on development of competitiveness.	Government

Geothermal potential was once considered to be determined only by high-temperature hydrothermal resources along tectonic plate boundaries, but low- and medium-temperature hydrothermal resources have also proven to be of value in geothermal heat applications or binary (combined heat and) power plants. Governments should therefore reconsider their countries' geothermal potential on the basis of a broader perspective that takes into account high-grade and low-grade hydrothermal resources as well as hot rock resources. They should then establish medium-term targets for (nearly) mature technologies and long-term targets for advanced technologies to exploit geothermal potential for heat and power and all types of resources.

Some geothermal power plants have already proven themselves to be competitive with newly built conventional power plants, where hydrothermal resources offer sufficiently high temperatures or electricity prices are high. Moreover, the base-load characteristic of geothermal power ensures that its increased deployment does not impose load balancing requirements on the electricity system. For geothermal technologies that are not yet commercially viable, however, because of high capital investments, clear, long-term, effective and predictable economic incentive schemes are required to provide sufficient investor confidence. These might include feed-in tariffs, feed-in premiums, renewable portfolio standards, fiscal incentives and investment subsidies, as well as framework conditions such as access to grids.

Feed-in tariffs and premiums for geothermal electricity already exist in several European countries (Box 9), while the first geothermal heat feed-in tariff will come into force in the United Kingdom in mid-2011, offering support to heat from deep geothermal resources at an initial level of about USD 0.05/kWh (GBP 0.03/kWh). The levels of feed-in tariffs or premiums must be carefully studied and agreed upon with all parties involved, private and public, as they are ineffective if too low and economically inefficient if too generous. Renewable portfolio standards can be effective if they are sufficiently ambitious and binding for utilities – that is, if the financial penalties are set at appropriate levels in case of little or no compliance with the targets. Renewable portfolio standards work particularly well for high temperature geothermal development but might need banding for less competitive geothermal technologies. While incentives need to be gradually reduced as geothermal capacities rise and costs fall, revisions need to be announced in advance.

Box 9: Geothermal feed-in tariffs in Germany

In Germany, good economic framework conditions exist for geothermal development, as the Renewable Energy Sources Act guarantees system operators fixed payments for geothermal electricity fed into the grid. As of January 2009, the feed-in tariff for geothermal plants with a plant capacity up to 10 MW is USD 0.23/kWh (EUR 0.16/kWh), and above 10MW it is USD 0.15/kWh (EUR 0.105/kWh). On top of this basic tariff, a bonus of USD 0.04/kWh (EUR 0.03/kWh) is available for geothermal CHP. If the plant starts running before 1 January 2016, an additional bonus of USD 0.06/kWh (EUR 0.04/kWh) is available. When using EGS technology, another additional USD 0.06/kWh (EUR 0.04/kWh) can be obtained.

In the most beneficial situation, a geothermal CHP plant of up to 10 MW running before 2015 and using EGS technology can receive a USD 0.39/kWh (EUR 0.27/kWh) feed-in tariff. The prevailing economic and political conditions have spurred geothermal development and geothermal CHP in Germany. At the end of 2010, 10 geothermal CHP plants were under construction in the Rhine Graben and Molasse Basin region, while applications for exploration permits had been submitted for a further 150 sites (Schmellschmidt *et al.*, 2010; www.erneuerbare-energien.de).

Incentives aiming for increasing renewable heat shares have thus far received less attention than those for renewable electricity.[11] The co-generation of electrical and thermal power from geothermal sources offers potential both for improved economic performance and for increased overall renewable energy usage. Recent innovative renewable heat approaches, such as the UK renewable heat feed-in tariff, deserve consideration.

11. Examples of policies specifically aimed at encouragement of renewable heat are Fond Chaleur (France, www.ademe.fr) and EEWärmeG (Germany, www.bmu.de).

Market facilitation and transformation

This roadmap recommends the following actions:	***Milestones***	***Stakeholder***
Introduce streamlined and time-effective permit procedures for geothermal plants and develop geothermal-specific procedures.	2011-15	Government.
Develop and use protocols to create community support for EGS and understanding about micro-seismicity.	2011-20	Geothermal/EGS developers and government.
Consider introduction of policies to cover the financial risk involved in geothermal exploration. Develop financial instruments covering this phase of geothermal development.	Start 2011	Government, development banks and commercial banks.
Enhance training, education and awareness for skilled work forces along the geothermal value chain; expand outreach to related professional groups.	Start 2011	Government, geothermal industry and research institutes.

Several non-economic barriers can significantly hamper the effectiveness of geothermal support policies; difficulties in obtaining permits, for example, can hinder new geothermal plants. Many countries that lack specific laws for geothermal resources currently process geothermal permits under mining laws that were conceived with objectives other than renewable energy production. Permitting procedures can consist of numerous steps, resulting in long lead times. The lack of regulation for geothermal energy is inhibiting the effective exploitation of the resource. Measures that have been successful include: enforcing legislation that separates geothermal resources from the mining code; geothermal rights clearance as part of a long-term concession in public tendering; and introducing simplified procedures consisting of fewer steps or even a "one-stop shop" approach.

Exploiting the potential of hot rock resources, *e.g.* by means of EGS, is crucial to realising the vision of this roadmap. However, induced micro-seismicity – the most critical potential side-effect of EGS – may hinder the development of such projects. Micro-seismicity is not new, however; is reported in all major underground activities, such as mining, constructing traffic tunnels, oil/gas production, and hydraulic fracturing in oil and gas reservoirs. Apart from increasing public understanding of induced seismicity in a tectonically complex environment, several steps can be taken by EGS developers. A protocol for development can prove helpful in identifying suitable locations for EGS and in creating community support (Box 10).

Box 10: Protocol for EGS development

A protocol for EGS development that was developed by the IEA Geothermal Implementing Agreement stresses the importance of:

- reviewing regulations, *e.g.* procedures to mitigate induced seismicity as included in mining laws;
- assessing natural seismic hazard potential by studying earthquake history, geological and tectonic setting, and earthquake statistics;
- assessing induced seismicity potential and preparing a mitigation plan;
- establishing continued dialogue with local authorities and local stakeholders;
- establishing a seismic monitoring network and implementing a procedure for evaluating damage.

If water flow rate and temperature are not high enough, geothermal development can fail, particularly if the necessary flow rate cannot be reached in low-temperature projects. The introduction of guarantee schemes for geothermal exploration productivity risks should be considered, although this may differ from region to region, depending on local conditions. Risk coverage schemes aim at reimbursing a certain percentage of the investments. In addition to a private risk insurance scheme in Germany (Schultz et al, 2010), several government approaches exist, *e.g.* in France, Germany and Switzerland (Rybach, 2010).

The French "Short-term Risk Guarantee", operating since 1981, secures reimbursement for all or part of the investment in the event of total or partial failure of the drilling operation. The "Long-term Risk Guarantee" allows coverage over a 25-year exploitation phase against the risk of decreasing or failing resources. In the Netherlands, a government exploration risk guarantee scheme was introduced in 2009. The revised scheme that came into force in 2010 offers a payment of 85% of exploration costs in case the productivity of the exploration well is less than 75% of the expected output. In Switzerland, backers of geothermal power projects at the final investment decision stage are encouraged to apply for a risk coverage scheme that may reimburse up to 50% of the total sub-surface development cost in case of failure to find suitable sub-surface resources (Siddiqi, 2011). The World Bank's Geological Risk Insurance (GRI) in Eastern Europe and Central Asia targets the risks associated with geothermal energy exploration and operation (Rybach, 2010). The US Loan Guarantee Program can also be used as an instrument to cover the risk of the exploration phase of geothermal development. Reservoir-risk insurance schemes reduce the need for equity through partial coverage of costs should the project become uneconomical and thus can be an important way of reducing geothermal development costs.

Given the high uncertainty in finding a geothermal resource when drilling, debt financing usually only becomes an option when the resource has been successfully proven. Government support and subsidies are, in some cases, helping to launch projects. On the open market, such options are limited, but specialised financial institutions have started to develop alternative financing instruments. One example is Islandsbanki's resource verification loan, which was used to cover the cost of drilling and testing two initial production wells for a geothermal power plant in California. Other innovative approaches have been reported where developers raise funds and/or receive in-kind project contributions from large corporations (BNEF, 2010).

For deep geothermal drilling and reservoir management, skilled companies and well-trained personnel are currently concentrated in just a few countries. As geothermal developments spread, demand for trained geothermal scientists and engineers will increase even in countries that currently have limited geothermal experience. This means that geothermal science and engineering programmes will need to be improved and expanded. Information exchange platforms within regions with geothermal resources should be enhanced to increase awareness of geothermal technology.

Research, development and demonstration support

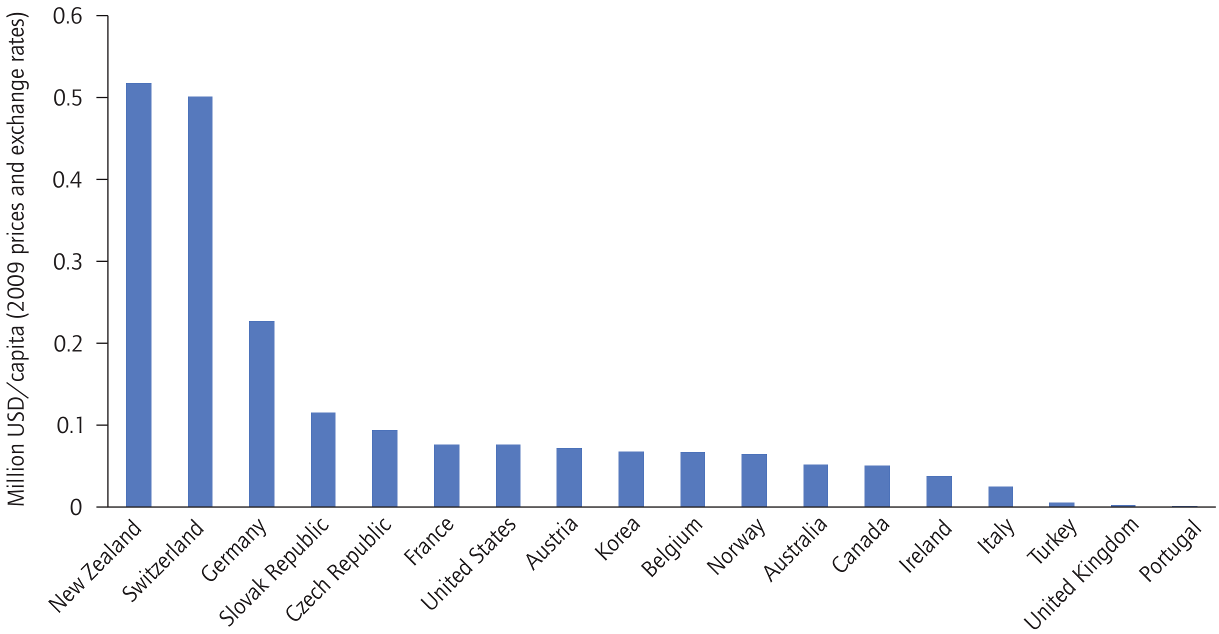
This roadmap recommends the following actions:	***Milestones***	***Stakeholder***
Increase public RD&D funding.	2011-20	Government.
Ensure sustained RD&D funding in the long-term, also through private-public partnerships.	2020-40	Government and private sector.

Geothermal energy technologies have differing levels of maturity. The exploitation of hot rock resources, *e.g.* by means of EGS which is currently in the demonstration phase, has particular potential for improvement. Long-term, sustained and substantially higher research, development and demonstration (RD&D) resources are needed to accelerate cost reductions and design, and bring novel geothermal concepts to market. These advanced technologies have to be proven in pilot plants, meaning that strong government support for innovative small plants is needed. In recent decades, public RD&D efforts have been undertaken in Europe – resulting in the European EGS test plant in Soultz-sous-Forêts, France – as well as in Australia and the United States. The engagement of the Australian government in developing pre-competitive geoscience information on geothermal resources has facilitated industry investments in the sector. The Australian government is also making investments in geothermal drilling and demonstration projects. Within the European Energy Research Alliance (EERA), a Joint Programme on Geothermal Energy (JPGE) is dedicated to join efforts in geothermal R&D over the next 10 years and will bring together over 250 scientists from 12 different European research organisations. Important R&D priorities for geothermal electricity and heat are:

- development of databases, protocols and tools for geothermal resource assessment;
- development of new and more competitive drilling technology as well as downhole instrumentation;

- increase efficiency and performance of geothermal CHP and expand possibilities for geothermal heat use;
- improve EGS technology and development of efficient reservoir creation and management methods;
- improve management of health, safety and environmental (HSE) issues, including risks associated with induced seismicity, in EGS development;
- explore feasibility of alternative hydrothermal and alternative hot rock technology.

Figure 15: Public RD&D budget for geothermal energy, 2006-09 average (million USD per capita)



Note: Where available, 2010 estimates are also included. US Recovery Act Spending for geothermal energy in 2009 are not included. IEA countries without geothermal RD&D spending are not included the graph.

Source: (www.iea.org/stats/rd.asp).

IEA countries' contributions to RD&D in geothermal energy have been modest or nil. On a per capita basis, New Zealand has highest RD&D spending dedicated to geothermal energy (Figure 15). New Zealand is also the only country to direct more than 10% of its total RD&D expenditures towards geothermal energy (IEA, 2010b). Several countries without conventional high-temperature hydrothermal resources dedicate considerable per capita RD&D spending to geothermal energy, *e.g.* Switzerland and Germany. In absolute numbers, highest averaged RD&D budgets over 2006 to 2010 are found in the USA (USD 23.1 million) and Germany (USD 18.6 million). The US Recovery Act spending on geothermal energy (not included in Figure 15) amounted to USD 174 million in 2009, increasing the annual RD&D budget for geothermal energy by seven times in that year.

Geothermal energy has received less interest in terms of RD&D spending than other renewable energy technologies. However, measuring performance improvement against cumulative public R&D investment suggests that geothermal energy may show major performance gains as a function of R&D investment and may become economically comparable with, if not superior to, fossil fuels with modest investment (Schilling and Esmundo, 2009).

The EGS pilot plants that will be needed in the next 10 years to realise the development of geothermal energy envisaged in this roadmap will include a very strong RD&D component, as they are supposed to be tested in different geological environments. This will require specific financial instruments (public-private partnerships and grants) and co-financing from public institutions (European Commission, international financing institutions, national and regional authorities, public funds), the private sector (investors, banks and the industry) and research institutes (ITRE, 2010).

In the short term, it is crucial to increase public RD&D funding to accelerate the geothermal deployment process, as basic research into the technology is still far from market and therefore less likely to be of interest to the private sector. Beyond 2020, increasing the involvement of the private sector, partly through innovative public-private partnerships, will be vital to achieving the required RD&D funding levels.

International collaboration and deployment in developing economies

This roadmap recommends the following actions:	***Milestones***	***Stakeholder***
Expand international R&D collaboration, making best use of national competencies.	Start 2011	Research institutes, universities, government, geothermal industry.
Develop mechanisms that address non-economic and economic barriers to geothermal development in developing countries.	Start 2011, phase out depending on development of competitiveness.	Development banks, NGOs, governments.
Expand the targeting of clean energy deployment.	Start 2011, phase out depending on development of competitiveness.	Development banks.

The global geothermal community is small but well connected and has found several means to collaborate intensively and ensure that knowledge is exchanged. Sustained co-ordination will be needed during the process of accelerated geothermal deployment as well as an increasing workforce of geothermal scientists, engineers and technicians. International collaboration will ensure that important issues are addressed according to areas of national expertise, taking advantage of existing RD&D activities and infrastructure. Long-term harmonisation of research agendas is also needed. One example of collaboration is the IEA Geothermal Implementing Agreement, one of 42 such initiatives covering the complete spectrum of energy technology development. The Geothermal Implementing Agreement includes technology experts from 13 countries, the European Union and five industries or industry organisations. It serves to share good practice among member countries and sponsors and to establish common research agendas on specific topics in a task-sharing manner at a high level. Participation by all countries with an interest in geothermal energy, whether IEA members or not, would further strengthen the Geothermal Implementing Agreement. Other examples of collaboration are the International Geothermal Association (IGA), the International Partnership for Geothermal Technology (IPGT), the Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs (GEISER) project and the Iceland Deep Drilling Project (IDDP).

Realising the full potential for global geothermal deployment requires particular attention to the needs of developing and emerging economies. A large share of known high-temperature geothermal resources are still unexploited in countries such as Indonesia and the Philippines, and in Central and South America and East Africa. Indonesia, in particular, offers enormous potential for geothermal energy. This immense volcanic archipelago is said to have a large share of worldwide high-temperature hydrothermal resources with just over 1 GW_e of installed electric power generation capacity so far and an estimated 27.5 GW_e still untapped (Box 11).

In the Philippines, too, there is a large, unexploited geothermal potential, with 2 GW_e generating capacity installed so far out of a total estimated potential of 4.5 GW_e. Since the introduction of the Renewable Energy Law in 2008, several foreign developers have entered the Philippine geothermal market. Although high-temperature hydrothermal resources in these markets might be considered "low-hanging fruit", their exploitation can be hindered by a diverse range of country-specific barriers. Non-economic barriers include long, complex permitting procedures, such as licences, environmental appraisals and difficulties to access power lines through interconnection rights; complications in negotiating a long-term power purchase agreement in a non-liberalised energy market; and unclear governmental responsibilities for geothermal resources. Economic barriers can arise when costs are forced up by a limited supply of local partners and vendors, or when remoteness of project sites increases the costs of drilling mobilisation and grid extension.

Support for geothermal energy in developing countries includes the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change, which enables industrialised nations to pay for CO_2 reductions in developing countries. In Indonesia, two geothermal projects, the Darajat 3 and the Kamojang 4 plant near Garut, West Java, have recently been deemed eligible for CDM credit funding. The Deutsche Bank Group recently explored the possibility of setting up a feed-in tariff scheme for developing countries, dubbed the GET FiT Programme (Deutsche Bank Group, 2010). The concept, still under development, is to establish a fund that is sponsored by international donors to provide premium payments for renewable energy in developing countries.

Innovative mechanisms need to be explored that address non-economic and economic barriers to geothermal development in developing countries. As well as development banks, NGOs have a role to play in raising awareness. It is also vital to build co-operation platforms among or between developing countries on policy reform, financing mechanisms, human resource development and technology. In Asia, examples are the Association of Southeast Asian Nations (ASEAN), the Asia-Pacific Economic Cooperation (APEC) and Indonesia's bilateral agreements with New Zealand and the Philippines.

Multilateral bank funding is ubiquitous in geothermal development as more and more projects are in developing countries; since 2005, USD 3.8 billion or 57% of all funding has been released in developing countries (BNEF, 2010b). Multilateral banks such as the Inter-American Development Bank (IADB), the European Investment Bank (EIB) and the International Bank for Reconstruction and Development (IBRD) rank high in the top 15 debt providers for new build geothermal asset finance (ibid.). Bilateral development banks , including the German state-owned KfW, the French Development Agency (AFD) and the Japan International Cooperation Agency (JICA) are also funding geothermal development worldwide. These sorts of targeted geothermal projects should be maintained and extended where possible.

Box 11: Case study: geothermal energy deployment in Indonesia

Geothermal energy in Indonesia today

Indonesia's rapidly developing economy, in combination with overcoming its currently low electrification rate of 64.5% in 2009 (IEA, 2010d) will contribute to a high electricity demand in the future. A significant producer and exporter of fossil fuels, the country also has the world's largest potential for hydrothermal geothermal electricity. Geothermal energy can play an important role in meeting Indonesia's commitment to reduce greenhouse gas emissions by 26% by 2020.

The current installed geothermal power capacity of 1 197 MW represents only about 4% of the estimated 28.5 GW geothermal electricity potential in Indonesia (Geological Agency / MEMR, 2010). Geothermal resources in Indonesia still consist of large shares of "low-hanging fruit" – resources with low exploration risks and temperatures high enough for flash plants. Economics of geothermal projects can be improved with the help of Carbon Emissions Reduction certificates from CDM.

Figure 16: Geothermal potential in Indonesia

Source: Geological Agency.

Vision for deployment

The Indonesian government has ambitious plans for geothermal energy. In its 2006 vision it planned to have 9.5 GW of geothermal installed by 2025 while in the 2010 update this goal was further increased to 12.3 GW by 2025. A ministerial regulation of January 27, 2010, also set up a short-term goal of 3 977 MW of new geothermal installation by 2014, which should help the country to keep pace with rapidly growing electricity demand.

Technological challenges

Since convective hydrothermal systems are still abundant and easily accessible at depths of 1.5 km to 2 km, their development is a first priority. Hot rock resources are believed to offer potential in Sumatra, Kalimantan and Papua but only in the long term (Geological Agency/MEMR, 2010), so technological priorities are to map hydrothermal potential more extensively and combine in one database geothermal data and data from oil and gas exploration (ibid.).

Box 11: Case study: geothermal energy deployment in Indonesia (continued)

Geothermal development procedures

Geothermal development in Indonesia can be hindered by the disconnection between those involved in electricity pricing for geothermal projects during the tender process and the power purchasing agreement (PPA) that will need to be agreed with PLN, the state-owned electric utility, later on. Geothermal producers can in general only sell power to PLN, although there are some emerging opportunities to sell directly to large industrial users. The price at which PLN sells power to its customers is set by the government, so PLN does not have economic incentives to buy geothermal power, as it will usually be more expensive than the electricity prices it is allowed to sell it for. Until 16 February 2011, geothermal projects were jeopardised financially by the risk that developers would not be able to agree on an acceptable PPA with PLN. From 16 February 2011, when MEMR Regulation no. 02/2011 was published, PLN is obliged "to purchase electrical power resulting from geothermal power plants in accordance with the price of electrical energy resulting from the auction of working areas of geothermal mining".

Permitting procedures can be complicated because local or regional authorities have recently acquired the right and responsibility to govern mineral and geothermal resources and sometimes lack experience with tendering procedures, which creates delays. In addition, many geothermal sites are in protected forest areas, so permitting procedures involve several different governmental departments. A third complication arises when tenders are done based on geological information that bidders may find insufficient, resulting in prices that may not reflect the real value of geothermal fields.

Recent developments in policy framework

In the MEMR regulation No. 2/2010, the details of the 3 977 MW new geothermal capacity planned for 2014 are set out, 78% of which is intended to be implemented by independent power producers (IPPs). To attract private sector investments, Indonesia implemented several geothermal policies in 2010, including tax holidays and exemptions from customs duty and VAT on imported geothermal technology. MEMR regulation No. 32/2009 announced a ceiling price of USD 97/MWh for PLN to purchase geothermal electricity from IPPs. Also, IPPs are now allowed to directly sell power to PLN, whereas before the IPP could produce steam but PLN would own the plant.

Indonesia set up a new Directorate General of Renewable Energy in August 2010 to "simplify and hasten" development, especially of geothermal energy (BNEF, 2010a). The directorate is exploring several policy proposals (MEMR, 2010), including introducing a portfolio standard obliging utilities to make geothermal power 5% of their generation capacity.

Conclusions and role of stakeholders

This roadmap has responded to requests from the G8 and other government leaders for more detailed analysis of the growth pathway for geothermal energy, a key energy source, within a portfolio of low-carbon energy technologies. It describes approaches and specific tasks regarding RDD&D; financing mechanisms; legal and regulatory frameworks; public engagement; and international collaboration. It provides regional projections for geothermal deployment from 2010 to 2050. Finally, this roadmap details actions and milestones to aid policy makers, industry, research institutes, as well as financial institutions, to implement geothermal energy (see also Table 1).

The geothermal roadmap is meant to be a process that evolves to take into account new technical and scientific developments, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that development efforts are on track to achieve the reductions in greenhouse-gas emissions that are required by 2050.

Below is a summary of actions needed by geothermal stakeholders, presented to indicate who should take the lead in specific efforts. In most cases, a broad range of actors will need to participate in each action. The IEA, together with government, industry and NGO stakeholders, will report regularly on the progress achieved toward this roadmap's vision.

Table 1: Summary of actions to be led by stakeholders

Stakeholder	Action items
Government	Implement publicly accessible geothermal resources databases.
	Set long-term targets for geothermal electricity and heat.
	Introduce economic incentive schemes for both electricity and heat until geothermal has reached full competitiveness.
	Introduce streamlined and time-effective permit procedures for geothermal development.
	Consider introduction of policies to cover the financial risk involved in geothermal exploration.
	Enhance training, education and awareness for skilled workforce.
	Increase public RD&D funding.
	Ensure sustained RD&D funding in the long term.
	Expand international R&D collaboration, making best use of national competencies.
	Develop mechanisms to support geothermal deployment in developing countries.
Research institutions and/or universities	Implement publicly accessible geothermal resources databases.
	Ensure integrated approach for EGS identification and potentials assessment.
	Develop geothermal tools and models for identifying suitable hot rock and hidden geothermal sites.
	Develop cheaper drilling technologies and new drilling methods that decrease costs.
	Improve hard rock and high temperature-high pressure drilling technology.
	Explore feasibility of alternative technologies to exploit hot rock resources.
	Explore feasibility of alternative technologies to exploit hydrothermal resources.
	Enhance training, education and awareness for skilled workforce.
	Expand international R&D collaboration, making best use of national competencies.

Stakeholder	Action items
Industry	
Geothermal	Ensure integrated approach for EGS identification and potentials assessment. Develop geothermal tools and models for identifying suitable hot rock and hidden geothermal sites. Increase efficiency and performance of combined heat and power production. Develop EGS pilot plants in different geological environments. Ensure production enhancement and resource sustainability of EGS. Improve management of health, safety and environmental (HSE) issues, including risk associated with induced seismicity. Scale up EGS plants to realise plants of 50 MW to over 200 MW at a single site. Explore feasibility of alternative technologies to exploit hot rock resources. Explore feasibility of alternative technologies to exploit hydrothermal resources. Develop and use protocol for community support for EGS and understanding micro-seismicity. Expand international R&D collaboration, making best use of national competencies.
Drilling	Develop cheaper drilling technologies and new drilling methods that decrease costs. Improve hard rock and high temperature-high pressure drilling technology. Improve downhole instrumentation and well monitoring and logging.
District heating	Increase efficiency and performance of combined heat and power production. Explore expansion of possibilities for geothermal heat use.
Hydrocarbon	Explore feasibility of alternative technologies to exploit hydrothermal resources (co-produced from gas and oil wells).
Financial institutions	
Commercial banks	Develop financial instruments to cover geothermal exploration.
Multi-lateral/ bi-lateral development banks	Develop mechanisms to support geothermal deployment in developing countries. Expand targeting clean energy deployment.

Appendix I: Assumptions for production cost calculations

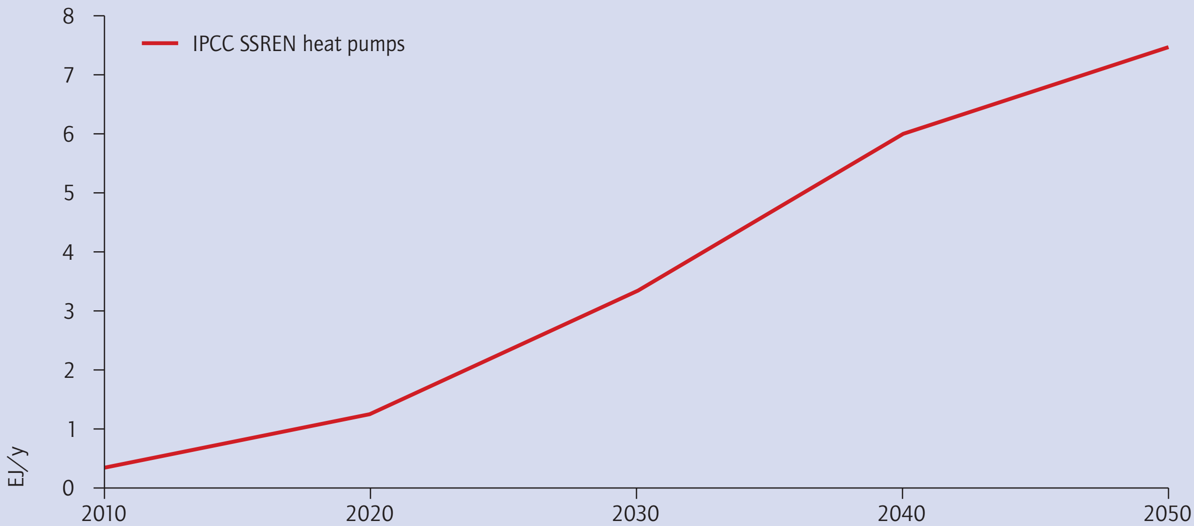
	Flash plants	Binary plants	District heating	Greenhouses
Investment costs (USD)	2000-4000/kW_e	2400-5900/kW_e	571-1566/kW_t	500-1000/kW_t
Capacity factor	85%	85%	50%	50%
Interest rate	10%	10%	10%	10%
Lifetime	35	35	25	20
O&M	2.5% of investment	2.5% of investment	2.0% of investment	2.0% of investment

Appendix II: Projected contribution of ground source heat pumps

Box 12: IPCC SSREN projection ground source heat pumps

This roadmap focuses on geothermal energy, excluding ground source heat pumps. However, it is acknowledged that ground source heat pumps (GSHP) are often ranked under geothermal heat production, such as in the European directive on the promotion of the use of energy from renewable sources (2009/28/EC). Projections for geothermal heat often include GSHPs. For that reason, this textbox shows – as an illustration of the potential of heat production by GSHPs and for reasons of benchmarking – the projection of the IPCC SRREN for GSHPs (IPCC, forthcoming 2011).

Figure 17: Indication of IPCC SSREN projection of global geothermal heat produced by ground source heat pumps up to 2050



Appendix III: Abbreviations, acronyms and units of measure

Abbreviations and acronyms

EGEC	European Geothermal Energy Council
EGS	Enhanced or engineered geothermal systems
EUR	Euro
GSHP	Ground Source Heat Pump
HSE	health, safety and environment
IEA-GIA	IEA Geothermal Implementing Agreement
IGA	International Geothermal Association
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RED	IEA Renewable Energy Division
USD	United States dollar

Units of measure

kW	kilowatt (10^3 Watt)
kW_e	kilowatt electric energy
kW_t	kilowatt thermal energy
MW	megawatt (10^6 Watt)
GW	gigawatt (10^9 Watt)
TW	terawatt (10^{12} Watt)
kWh	kilowatt-hour
MWh	megawatt-hour
GWh	gigawatt-hour
TWh	terawatt-hour
TJ	terajoule (10^{12} Joule)
PJ	petajoule (10^{15} Joule)
EJ	exajoule (10^{18} Joule)
Mt	Megatonnes

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