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GREAT EXPECTATIONS FOR GEOTHERMAL ENERGY TO 2100

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ABSTRACT

Geothermal energy systems: have a modest environmental footprint; will not be impacted by climate change; and have potential to become the world's lowest cost source of sustainable renewable thermal fuel for zero-emission, base-load direct use and power generation. Displacement of more emissive fossil energy supplies with geothermal energy can also be expected to play a key role in advancing both energy security and climate change mitigation strategies.In this context, shared challenges on the road to a global portfolio of safe, secure, competitively priced energy supplies are drivers for international cooperation in research, exploration, pilot demonstration and pre-competitive development of geothermal energy resources and technologies.

The intellectual and financial inputs for international, pre-competitive initiatives are coming from public and private investors with aspirations for low emissions, affordable, and globally deployable 24/7 energy supplies. It is reasonable to conclude that the outcomes (improved technologies and methods) of these collective efforts over the next 20 years will underpin great expectations for widespread, profitable and environmentally sustainable use of geothermal energy for centuries to come. This paper provides a synopsis of recent findings including estimates of theoretical, technical, economic, developable geothermal energy resources and existing supplies for both power generation and direct use, and the objectives of notable international fora enabling cooperation to reduce impediments to widespread use of geothermal energy. Key conclusions are:

- Engineered Geothermal Systems are expected to fuel roughly half of an expected supply of 4.6 EJ per year (~160 GWe) of geothermal power generation by 2050, and potentially up to 32.4 EJ per year by 2100.
- Geothermal energy can conservatively be expected to meet:
  - more than 3% of the total global demand for electricity by 2050 and potentially more than 10% by 2100; and
  - about 5% of the global demand for heating and cooling by 2050 and potentially, more than 10% by 2100
- The technical potential of geothermal energy is enormous (118 EJ/yr to 3km and 1,109 EJ/yr to 10km for electricity and 10 to 312 EJ/yr for direct use in context of 315 EJ/yr average heat flux at 65 mW/m^2). Resources size is clearly not a limiting factor for global geothermal energy development; and
- With its natural thermal storage capacity, geothermal is especially suitable for supplying both base-load electric power generation and for fully dispatchable heating and cooling applications in buildings.

INTRODUCTION

Geothermal energy systems: have: a modest environmental footprint; will not be impacted by climate change; and have potential to become the world's lowest cost source of sustainable renewable thermal fuel for zero-emission, base-load direct use and power generation. Displacement of more emissive fossil energy supplies with geothermal energy can also be expected to play a key role in advancing both energy security and climate change mitigation strategies.In this context, shared challenges on the road to a global portfolio of safe, secure, competitively priced energy supplies are drivers for international cooperation in research, exploration, pilot demonstration and pre-competitive development of geothermal energy resources and technologies.

The intellectual and financial inputs for international, pre-competitive initiatives are coming from public and private investors with aspirations for low emissions, affordable, and globally deployable 24/7 energy supplies. It is reasonable to conclude that the outcomes (improved technologies and methods) of these collective efforts over the next 20 years will underpin great expectations for widespread, profitable and environmentally sustainable use of geothermal energy for centuries to come. This paper provides a synopsis of recent findings including estimates of theoretical, technical, economic, developable geothermal energy resources and existing supplies for both power generation and direct use, and the objectives of notable international fora enabling cooperation to reduce impediments to widespread use of geothermal energy.

Figure 1 Geothermal-electric installed capacity by country in 2009. The map of plate boundaries and heat flow comes from Hamza et al., 2008, and is used with kind permission from Springer Science+Business Media B.V.. The capacity data is from Bertani, 2010.

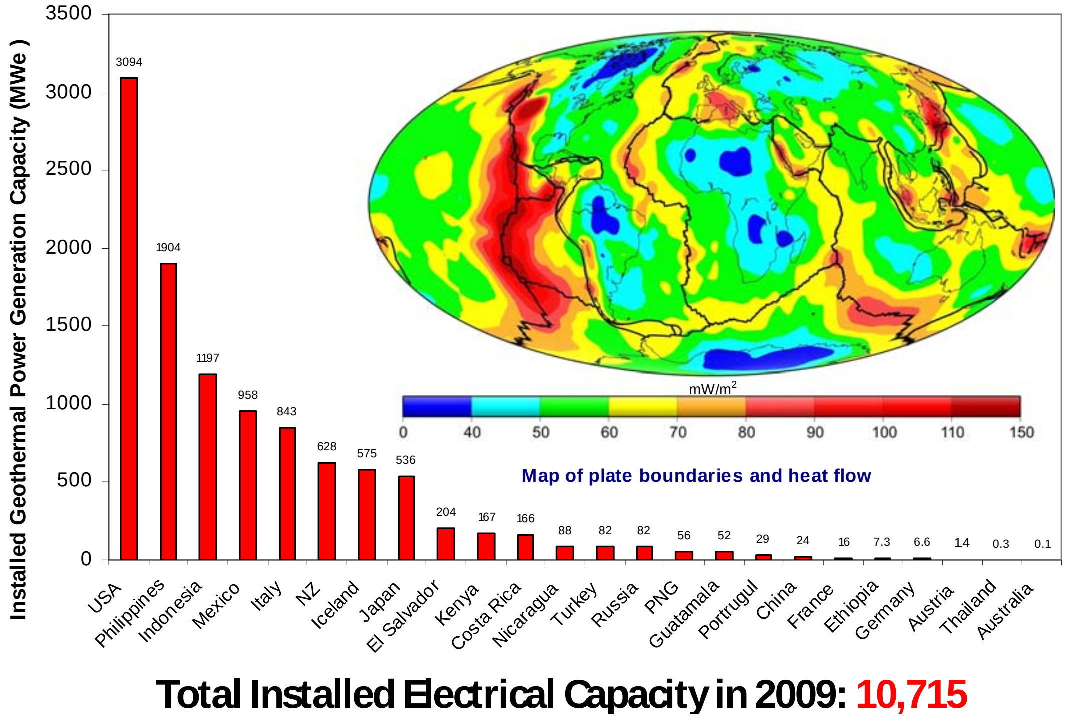
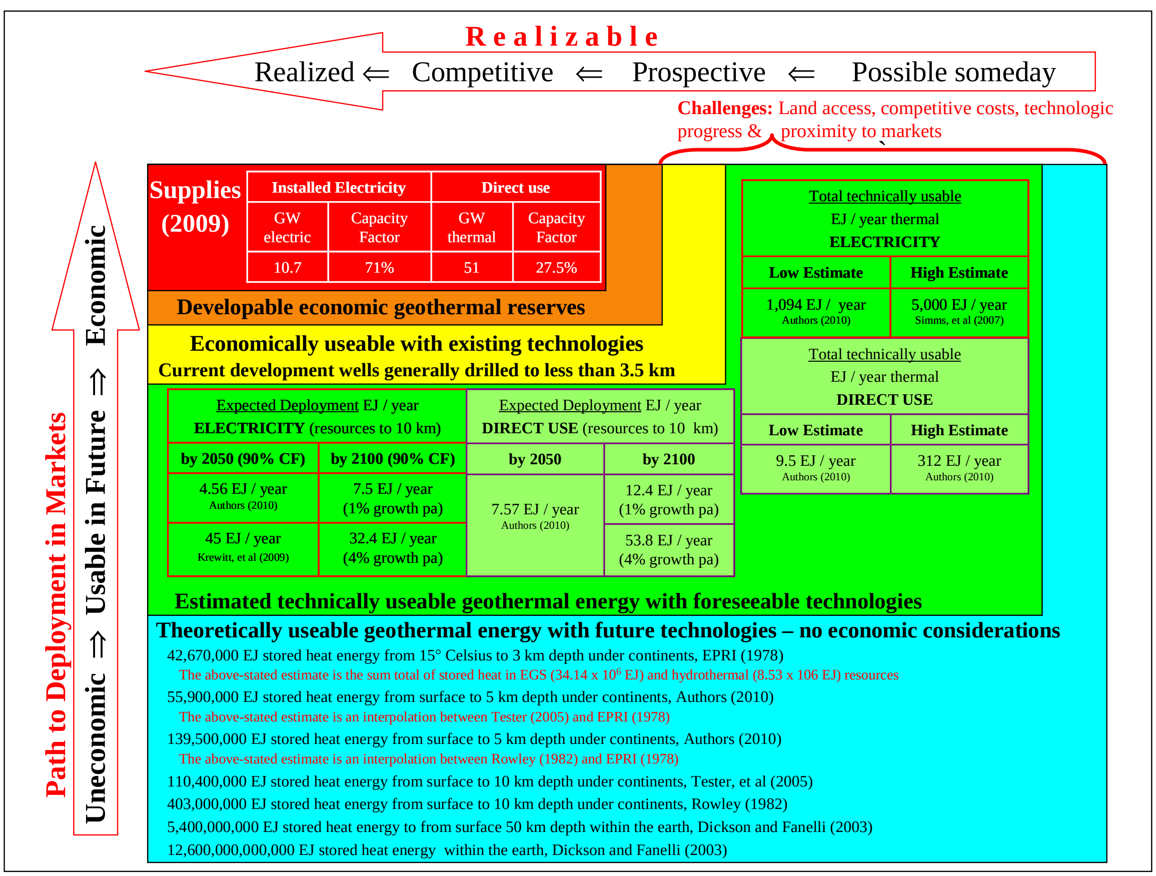


Figure 2. Potential geothermal energy resources split into categories e.g. theoretical, technical, economic, developable and existing supplies for power generation and direct use. This is an adaptation of a figure developed by Ladsi Rybach and published in Mongillo (2010)



SHARED KNOWLEDGE AND CHALLENGES BEGET COMPLEMENTARY ACTION

The co-authors of this paper support one or more of the international geothermal energy fora listed in Table 1.

Table 1. Ten key international geothermal energy fora

International Energy Agency's Geothermal Implementing Agreement (IEA GIA)	http://www.iea-gia.org/
International Geothermal Association (IGA) and its World Geothermal Congress (WGC) [(a)]	http://www.geothermal-energy.org/
International Partnership for Geothermal Technologies (IPGT) [(a)]	http://internationalgeothermal.org/
Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs (GEISER)	http://www.geiser-fp7.eu/default.aspx
ENhanced Geothermal Innovative Network for Europe (ENGINE)	http://engine.brgm.fr/
European Energy Research Alliance Joint Programme on Geothermal Energy (EERA JPGE)	http://www.eera-set.eu/index.php?index=36
European Geothermal Energy Council (EGEC)	http://www.egec.org/
Geothermal Resource Council (GRC) and its annual conference in particular	http://www.geothermal.org/
Geothermal Resource Association (GEA)	http://www.geo-energy.org/
Stanford University Geothermal Workshops	http://pangea.stanford.edu/ERE/research/geoth/conference/workshop.html
International Panel for Climate Change (IPCC) Working Group III – Special Report on Renewable Energy (and in particular Chapter 4 – Geothermal)	http://www.ipcc-wg3.de/publications/special-reports/special-report-renewable-energy-sources

Improved, evermore reliable, cost-effective methods to enhance the productivity of geothermal systems will be essential to the competitiveness of geothermal resource in energy markets. In particular, the commercialisation of fracture and/or chemical stimulation methods to reliably create Engineered (Enhanced) Geothermal Systems (EGS) will be one key milestone on the road to great expectations for widespread economic use of geothermal energy. Objectives of key international geothermal energy fora define the high priorities summarized in Table 2.

Table 2. High priorities to underpin advances in the use of geothermal energy, updated from Goldstein et al., 2009.

○ Openness to cooperation to engender complementary research and the sharing of knowledge	○ Informing industry people, government policy makers and the public
○ Creating effective standards for reporting geothermal operations, resources and reserves	○ For EGS, improved hard rock drill equipment
○ Predictive reservoir performance modeling	○ For EGS, improved multiple zone isolation
○ Predictive stress field characterization	○ For deep EGS, reliable submersible pumps
○ For EGS, mitigate induced seismicity	○ Longevity of well cement and casing
○ Condensers for high ambient-surface temperatures	○ For EGS: Optimum fracture stimulation methods
○ Use of CO_2 as a circulating fluid	○ High temperature logging tools and sensors
○ Improve power plant design	○ High temperature flow survey tools
○ Technologies & methods to minimize water use	○ High temperature fluid flow tracers
○ Predict heat flow and reservoirs ahead of the bit	○ Mitigation of formation damage, scale and corrosion

WORLD REPORT - GEOTHERMAL ENERGY USE

Geothermal energy supplies are currently used to generate base-load electricity in 24 countries with an installed capacity of 10.7 gigawatts of electricity (GWe) and a global average capacity factor of 71%, with newer installations above 90%, providing 10% to 30% of their electricity demands in six countries (Bromley, et al 2010). Figure 1 provides a map of crustal plate boundaries, estimated heat flow in milliwatts per square metre ($Wx10^{-6}/m^2$) and a histogram of geothermal electricity generation capacity by country. This heat flow map is imperfect, and a rendition that is more representative of all available local information remains an ambition of the authors.

Geothermal energy supplies are also used for direct use applications in 78 countries, accounting for 50.6 GW thermal (GW_{th}) including district (space) heating and cooling and ground-source (geothermal) heat pumps (GHPs), which have achieved significant market penetration worldwide (Lund et al.,2010).

BUILD (INNOVATE) AND MARKET BETTER MOUSE-TRAPS

The obvious generalised impediments to massive, global geothermal energy use are:

- currently insufficiently predictable reliability of geothermal reservoir performance (and in particular, the predicable reliability of EGS reservoirs); and
- current costs of geothermal well deliverability (and in particular, fluid production levels from stimulated engineered geothermal systems and the high costs of drilling deep wells

Hence, the over-arching common and well justified objectives of global government initiatives are to stimulate technologic and learn-while-doing breakthroughs that will lead to a point where the cost of geothermal energy use is reliably cost-competitive and comparatively advantageous within markets.

MARKET (COMMUNICATE!)

Geothermal resources contain thermal energy that can be produced, stored and exchanged (flowed) in rock, gas (steam) and liquids (mostly water) in the subsurface of the earth.

With proper management practice, geothermal resources are sustainable and renewable over reasonable time periods. As stored thermal energy is extracted from local regions in an active reservoir, it is continuously restored by natural conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by reinjection of the exhausted fluids.

Additionally:

- geothermal plants have low- to emissions-free operations and relatively modest land footprints. The average direct emissions yield of partially open cycle, hydrothermal flash and direct steam electric power plants yield is about 120 g CO_2/kWhe[1]. Current binary cycle plants with total reinjection yield less than 1 g CO_2/kWhe in direct emissions. Emissions from direct use applications are even lower (Fridleifsson et al., 2008). Over its full life-cycle (including the manufacture and transport of materials and equipment), CO_2-equivalent emissions are (generally): less than 50 g/kWhe for current operating geothermal power plants (based on Authors, 2010); less than 80 g/kWht for EGS power plants; and 14-202 g/kWht for district heating systems and GHPs (based on Kaltschmitt, 2000). This means geothermal resources are environmentally advantageous and the net energy supplied more than offsets the environmental impacts of human, energy and material inputs;

- geothermal electric power plants have characteristically high capacity factors; the average for power generation in 2009 is 71% (67,246 $GWh_{electrical}$ used from installed capacity of 10.714 $GW_{electrical}$ based on Bertani, 2010), and modern geothermal power plants exhibit capacity factors greater than 90%. This makes geothermal energy well suited for base-load (24/7), dispatchable energy use;
- the average estimated 27.8% capacity factor for direct use in 2009 (121.7 $TWh_{thermal}$ used from installed capacity of 50.6 $GW_{thermal}$ based on Lund, et al., 2010) can be improved with smart grids (as for domestic and industrial solar energy generation), by employing combined heat and power systems, by using geothermal heat absorptive and vapour compression cooling technology, and by expanding the distributed use of ground source heat pump energy generation; and
- properly managed geothermal reservoir systems are sustainable for very long term operation, comparable to or exceeding the foreseeable design-life of associated surface plant and equipment.

CHARACTERISING GEOTHERMAL RESOURCES, RESERVES AND SUPPLIES

The theoretical global geothermal resource base corresponds to the thermal energy stored in the Earth's crust.

The technical (prospective) global geothermal resource is the fraction of the earth's stored heat that is accessible and extractable for use with foreseeable technologies, without regard to economics. Technical resources can be subdivided into three categories in order of increasing geological confidence: inferred, indicated and measured (AGEG-AGEA, 2009), with measured geothermal resources evidenced with subsurface information to demonstrate it is useable.

Geothermal reserves are the portion of geothermal resources that can confidently be used for economic purposes. Geothermal reserves developed and connected to markets are energy supplies. Current geothermal power generation averages 71% capacity factor with an estimated 8.1% average efficiency for converting thermal into electrical energy. Both factors will improve (increase) in future, with modern power plants demonstrating 90% capacity factors.

Estimates of global stored heat to 10km by Tester, et al (2005) and Rowley (1982) are the basis for estimates of the technical potential of geothermal resources for electricity generation as summarised in figure 2.

Linear interpolations between resource estimates down to 3 km and 10km are the basis for the Authors (2010) range of estimates for the technical resource potential down to 5 km (as summarised in figure2).

All direct use estimates assume an average 31% capacity factor, somewhat higher than the average (27.5%) in 2009.

Accessible geothermal resources are enormous as detailed in Figure 2. Resources size is clearly not a limiting factor for global geothermal energy development.

FAQ: WHAT IS GEOTHERMAL ENERGY AND HOW DOES IT WORK? (COMMUNICATE!)

Geothermal energy is the terrestrial heat stored in, or discharged from rocks and fluids (water, brines, gases) saturated pore space (including fractures), and is widely harnessed in two ways: for power (electricity) generation; and for direct use e.g. heating, cooling, aquaculture, horticulture, spas and a variety of industrial processes, including drying. The use of energy extracted from the constant temperatures of the earth at shallow depth by means of geothermal heat pumps (GHP[2]) is a common form of geothermal energy use. The direct use of natural flows of geothermally heated waters to surface have been practised at least since the Middle Palaeolithic (Cataldi, 1999), and industrial utilisation began in Italy by exploiting boric acid from the geothermal zone of Larderello, where in 1904 the first kilowatts of electric energy (kWe) were generated and in 1913 the first 250-kWe commercial geothermal power plant was installed (Burgassi, 1999).

Where very high temperature fluids (> 180° C) flow naturally to surface (e.g. where heat transfer by conduction dominates), geothermal resources are the manifestation of two factors:

- a geologic heat source to replenish thermal energy; and
- a hydrothermal reservoir that can be tapped to flow geothermal fluids for its direct use and/or for generating electricity.

Elsewhere, a third geologic factor, the insulating capacity of rocks (acting thermal blankets) is an

[1] This is the weighted average of 85% of the world power plant capacity, according to Bertani and Thain, 2002, and Bloomfield et al., 2003

[2] Also referred to as ground source heat pumps (GSHP)

additional necessary natural ingredient in the process of accumulating usable, stored heat energy in geologic reservoirs that can be tapped to flow heat energy, and replenished by convective, conductive and radiated heat flow from sources of geothermal energy.

Usable geothermal systems occur in a variety of geological settings. These are frequently categorized as follows:

1. High-temperature (>180°C) systems at depths above (approximately) 3.5 km are generally associated with recent volcanic activity and mantle hot spot anomalies.. Other high temperature geothermal systems below (approximately) 3.5 km are associated with anomalously high heat producing crustal rocks, mostly granites;

2. Intermediate temperature systems (100-180°C); and

3. Low temperature (<100°C) systems.

Both intermediate and low temperature systems are also found in continental settings, formed by above-normal heat production through radioactive isotope decay; they include aquifers charged by water heated through circulation along deeply penetrating fault zones. However, there are several notable exceptions to these temperature-defined categories, and under appropriate conditions, high, intermediate and low temperature geothermal fields can be utilised for both power generation and the direct use of heat. Also, solar energy absorbed at the surface is sometimes included as geothermal energy, irrespective of its different source of heat energy. Offshore geothermal resources are also sometimes included in lists of ocean energy systems (Hiriart, et al, 2010).

Geothermal systems can also be classified as: *convection-dominated systems*, which include liquid- and vapour-dominated hydrothermal systems; conduction-dominated systems which include hot rocks; and hybrid systems that are sourced from convection, conduction and high heat producing source rocks. Geologic aquifers that overlie radiating sources of heat, and gain heat via convection and/or conduction are sometimes calls hot sedimentary aquifer systems.

The most widely recognised manifestations of geothermal energy are related to convective heat flow, including: hot springs and geysers (e.g. the movement of hot water to land surface); volcanoes (e.g. the movement of magma to land surface and sea floors); and certain forms of economically significant minerals deposits resulting from the injection of geothermally heated fluids into lower temperature levels where minerals crystallize and are accumulated.

Geothermal wells produce naturally hot fluids contained in hydrothermal reservoirs from a continuous spectrum of natural high to low permeability and porosity (including natural fractures). The capacity of geothermal reservoirs to flow hot fluids can be enhanced with hydraulic fracture stimulation and acidization, creating artificial fluid pathways in Enhanced or Engineered Geothermal Systems (EGS) as well described in detail in Tester, et al (2006). Once at surface, heated fluids can be used to generate electric energy in a thermal power plant, or used in other applications requiring heat, as heating and cooling of buildings, district heating systems, aquaculture, agriculture, balneology, industrial processes and mineral drying. Space heating and cooling can also be achieved with GHP systems.

The number, depth and diameter of geothermal energy production wells vary with local requirements for direct use and electricity power plants. Higher temperatures and higher flow rates result in more thermal energy production per well. Wells drilled to depths down to about 3.5 km in volcanic areas frequently produce high temperature (> 180°C) fluids to surface. Indeed, temperatures above 1000°C can occur at less than 10 km depth in areas of magma intrusion. Given the global average land area surface temperature of (about) 15°C and an approximate global geothermal temperature gradient for land areas outside volcanic settings of (about) 30°C per kilometre, the same high temperature (> 180°C) can be reached (on average) at a depth of about 5.5 km below ground level.

The main types of geothermal power plants use direct steam (often called dry steam), flashed steam and binary cycles.

Power plants that use dry and/or flashed steam to spin turbines are the most commonly deployed form of geothermal electricity generation. These plants use the heat energy contained in water and steam flowed from geothermal wells to spin turbines, converting thermal and kinetic energy to electrical energy.

Organic Rankine power plants employing secondary working fluids are increasingly being used for geothermal power generation. These so-called binary closed-loop power plants do not flow produced geothermal fluids directly into turbines. Thermal energy contained in water and/or steam produced from geothermal wells is transferred to a secondary working fluid using a heat exchanger (hence the term binary closed-loop). Organic compounds with lower boiling points than water (such as propane that boils at about 28°C are often used as working fluids. The heat energy in the geothermal fluid boils the working fluid changing it from a liquid to a pressurized gas within the closed-loop, which can then be expanded in a turbine to spins a generator. The exhausted working fluid is cooled, condensed back into a liquid, pressurized and then recycled into the heat exchanger to complete the cycle.

Table 1 Estimated global long term forecasts of installed capacity for geothermal power and direct uses (heat) and of electric and direct uses (heat) generation from Bertani, 2010 and Authors, 2010.

Expected World Use	2020		2030		2050		2100	
	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)	Direct (GWt)	Electric (GWe)
Capacity	160.5	25.9	455.9	51.0	800	160.6	1,316 to 5,685	264 to 1,141
Expected global use	TWh_t/y	TWh_e/y	TWh_t/y	TWh_e/y	TWh_t/y	TWh_e/y	TWh_t/y	TWh_e/y
	421.9	181.8	1,998.0	380.0	2102.2	1266.4	3,457 to 14,940	2,083 to 9,000
	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y	EJ/y
	1.52	0.65	4.31	1.37	7.57	4.56	12.4 to 53.8	7.5 to 32.4

Table 2 World installed capacity, electricity production and capacity factor of geothermal power plants 1995-2010, forecasts for 2015-2050 (adapted from data from Bertani, 2010 and Authors, 2010) and forecasts for 2100 based on 1% and 4% average annual growth for 50 years from 2050.

Year	Installed Capacity (GWe) Actual or mean forecast	Electricity Production (GWh/y) Actual or mean forecast	Capacity Factor (%)
1995	6.8	38,035	64
2000	8.0	49,261	71
2005	8.9	56,786	73
2010	10.7	67,246	71
2015	18.5	121,600	75
2020	25.9	181,800	80
2030	51.0	380,000	85
2040	90.5	698,000	88
2050	160.6	1,266,400	90
2100	264 to 1,141	2,082,762 to 8,999,904	90+

Table 3. Range of technical recoverable heat energy from accessible geothermal resources

Probability		99%	90%	50%	Log-normal mean	10%	1%
Recovery Factor		0.05%	1.34%	4.47%	7.00%	14.95%	40.00%
Accessible Stored Thermal Energy Estimates	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6	EJ x 10^6
< 10 km under continents (Rowley, 1982)	403.0	0.2	5.4	18.0	28.2	60.2	161.2
< 10 km under continents (Tester, et al 2005)	110.4	0.1	1.5	4.9	7.7	16.5	44.2
<5 km under continents (Authors, 2010[3])	139.5	0.1	1.9	6.2	9.8	20.9	55.8
<5 km under continents (Authors, 2010[4])	55.9	0.03	0.7	2.5	3.9	8.4	22.4
15 degrees C to 3 km under continents (EPRI, 1978)	42.7	0.02	0.6	1.9	3.0	6.4	17.1

HOW BIG WILL GEOTHERMAL BE? (COMMUNICATE!)

The extent or accessibility of geothermal resources will not be a limiting factor for deployment. Tables 1 and 2 summarize the conclusions reached by the co-authors in 2010). These forecasts assume improvements in capacity factors power generation from the current average 71% to at least 90% by 2050, a level already attained in efficient, existing geothermal power generation plants. Earlier estimates for deployment beyond 2010 that were considered in developing forecasts in Table 1 include: IPCC, 2007; IEA, 2008; and EREC, 2008.

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[3] Based on interpolation between Rowley (1982) to 10km and EPRI (1978) to 3 km

[4] Based on interpolation between Tester (2005) to 10km and EPRI (1978) to 3 km

CONCLUSIONS - DEPLOYMENT BY 2100

Current global trends and regional research underpin credible expectations for great growth in the global use of geothermal energy over the next 90 years. Great expectations are:

- Power generation with binary plants and total re-injection will become common-place in countries without high-temperature resources.
- Geothermal energy utilization from conventional hydrothermal resources continues to accelerate and the advent of EGS is expected to rapidly increase growth after 10 to 15 years putting geothermal on the path to provide an expected generation global supply of 4.56 EJ per year (~160 GWe) by 2050, and between 7.5 EJ per year (with 1% growth per year) and 32.4 EJ per year (with 4% growth per year) by 2100.
- In addition to the widespread deployment of EGS, the practicality of using supercritical temperatures and offshore resources is expected to be tested with experimental deployment of one or both a possibility by 2100.
- Direct use of geothermal energy for heating and cooling, including geothermal heat pumps (GHPs) is expected to increase to 7.57 EJ /year (~800 GWt) by 2050 and between 12.4 EJ per year (with 1% growth per year) and 53.8 EJ per year (with 4% growth per year) by 2100. Marketing and multiple internationally competitive supply chains will underpin this growth. These expectations are supported with information published by Rybach, 2005
- Geothermal energy is conservatively expected to meet between 2.5% and 3.1% of the total global demand for electricity by 2050 and potentially more than 10% by 2100. It is also conservatively expected to provide about 4.7% of the global demand for heating and cooling in by 2050 and potentially, more than 10% by 2100. Geothermal energy will be a dominant source of base-load renewable energy in many countries in the next century.
- With its natural thermal storage capacity, geothermal is especially suitable for supplying both base-load electric power generation and for fully dispatchable heating and cooling applications in buildings, and thus is uniquely positioned to play a key role in energy security and climate change mitigation strategies (Bromley, et al., 2010).

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