Great Expectations for Geothermal to 2100 – Messages for Now

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Keywords

Geothermal energy, capacity factor, ground source heat pumps, radiated heat flow, convection-dominated systems, conduction-dominated systems, and EGS

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. As for the here and now:

- At year-end 2010, geothermal base-load power is used in 24 nations. The global installed capacity is ~11 $GW_{electric}$ with an average 75% capacity factor and > 90% capacity factor in modern plants;
- At year-end 2010, geothermal energy direct uses are deployed in 78 nations; amounting to ~ 50 $GW_{thermal}$ with an average 27.5% capacity factor;
- In 2005-09, global geothermal energy use increased by ~4% pa for electricity and by ~10% pa for direct-use, while direct use from geothermal heat pump production increased by ~ 20% pa;
- Flash power plants yield about 120g $CO2/kWh_{electric}$. Current binary cycle plants with total reinjection yield less than 1 g $CO2/kWh_{electric}$. Emissions from direct use applications are even lower; and
- The extraction of geothermal energy can be fully or partially replenished over the long term by the continental terrestrial heat flow of 315 EJ/y at an average flux of 65 mW/m^2 (Stefansson, 2005).
- Hot rocks are everywhere, so enhanced (engineered) geothermal systems (EGS) pose great global promise for the future supply of emissions-free base-load power.

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)

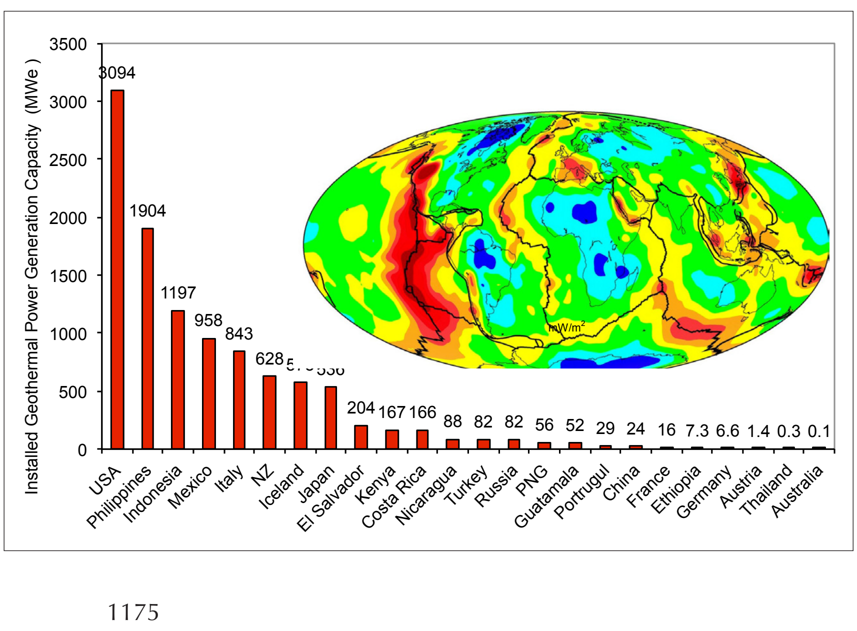

Figure 1. Geothermal-electric installed capacity by country in 2009. This figure also depicts global average heat flow in mW/m2 and tectonic plate boundaries (black lines). The map is adapted from a figure in Hamza et al., 2008 and the statistics are from Bertani, 2010.This map of heat flow does not reconcile all geothermal information. The delineation of geothermal resources will be improved by integrating temperature gradient, heat flow and reservoir data.

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 $GW_{electric}$) 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/m2). 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.

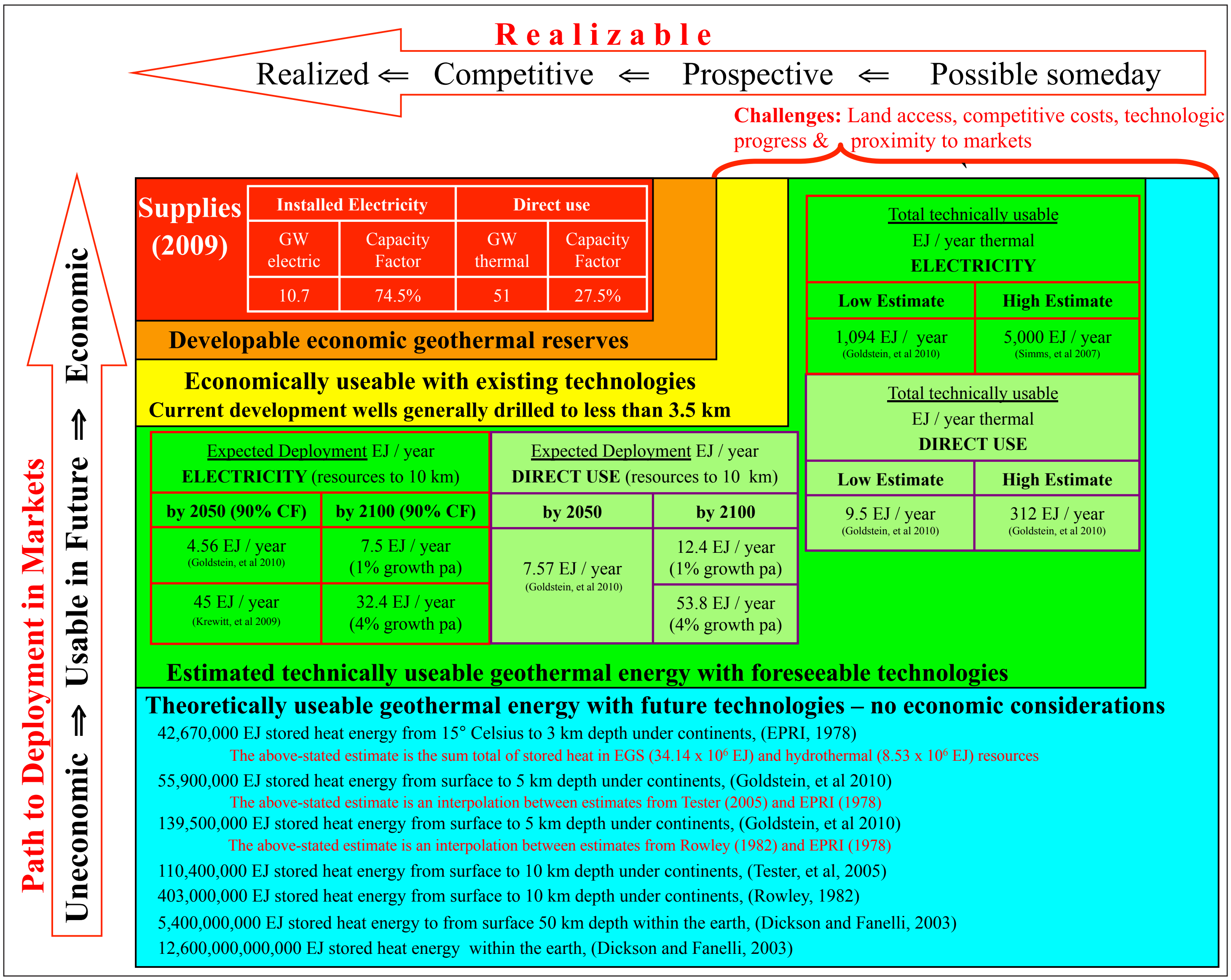

Figure 2. Potential geothermal energy resources split into categories e.g. theoretical, technical, economic, developable and existing supplies for power generation and direct use. All categories for power generation assume a 74.5% capacity factor and 8.1% average efficiency for converting thermal into electrical energy, though both factors will likely improve (increase) in future. All direct use estimates for the future assume an average 31% capacity factor, somewhat higher than the average (27.5%) in 2009. Adapted from Rybach, 2010 and M.A. Mongillo, 2010.

International desires for economic, energy security and environmental sustainability are expected to continue to drive investment in learning curves for evermore efficient and widespread development and use geothermal energy. A step-change to more sustainable energy security is expected from the commercialization of technologies that will enable the widespread production of heat energy from both deep non-magmatic hot rocks and offshore magmatic resources.

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.

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 Resources Council (GRC) and its annual conference in particular	http://www.geothermal.org/
Geothermal Energy 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

Shared Knowledge — Challenges Beget Complementary Action

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

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) independent of site conditions 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 of technologic advances and the merits of using geothermal energy through presentations, publications, websites, submissions to enquiries and the convening of conferences, workshops and courses
Creating effective standards for reporting geothermal operations, resources and reserves	For EGS, improved hard rock drill equipment
Predictive reservoir performance modelling	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 drill 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 ($GW_{electric}$) 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 of thermal energy ($GW_{thermal}$) 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 $CO2/kWh_{electric}$. Current binary cycle plants with total reinjection yield less than 1 g $CO2/kWh_{electric}$ 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), CO2-equivalent emissions are (generally): less than 50 g/ $kWh_{electric}$ for current operating geothermal power plants (based on Goldstein, et al, 2011); less than 80 $g/kWh_{thermal}$ for EGS power plants; and 14-202 $g/kWh_{thermal}$ 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 $GW_{electric}$ 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 (heat in place).

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.

At year-end 2010, geothermal energy supplies were used to generate base-load electricity in 24 countries with an installed capacity of nearly 11 gigawatts of electricity ($GW_{electric}$) and a global average capacity factor of nearly 75%, with newer installations above 90%, providing 10% to 30% of their electricity demand in six countries (Bertani, 2010). Figure 1 provides the geothermal electricity generation capacity by country and the mapped (estimated) distribution of global heat flow in milliwatts per square metre (mW/m^2).

In the 40 year term 1970 – 2009, the average annual growth of geothermal-electric installed capacity is 7% per annum; and n the 35 year term 1975 – 2009 the average annual growth for geothermal direct use is 11% per annum (Bertani, 2010; Lund et al, 2010; Lund et al, 2005; Garwell and Greenberg; 2007, and Fridleifsson and Ragnarsson, 2007).

At year-end 2010, geothermal energy supplies are also used for direct use applications in 78 countries, accounting for 50 $GW_{thermal}$ including district (space) heating and cooling and geothermal (ground-source) heat pumps, which have achieved significant market penetration worldwide (Kaltschmitt, 2000).Geothermal-electric installed capacity by country in 2009.

The total thermal energy contained in the Earth is on the order of 12.6 x 10^{12} EJ and that of the crust on the order of 5.4 x 10^9 EJ to depths of up to 50 km based on the estimates of Dickson and Fanelli (2003). Estimates of the stored thermal energy under continents within 10 km, 5 km and 3 km depth (all depths reachable with current drilling technology), has been estimated by EPRI (1978), Goldstein (2010), Tester (2005), Rowley (1982), and Dickson and Fanelli (2003) as presented in figure 2.

The stored thermal energy within 50km, (5.4 x 10^9 EJ as determined by Dickson and Fanelli, 2003) is approximates the theoretically useable geothermal energy within the earth.

Budd et al. (2008) estimated that recovery of just 1% of the stored geothermal energy above 150°C to 5 km in the Australian continental crust corresponds to 190,000 EJ. Based on these estimates, the theoretically available resource is enormous and clearly not a limiting factor for global geothermal deployment.

Geothermal Energy is an Enormous Renewable Resource

The main sources of this energy are due to the heat flow from the earth's core and mantle, and that generated by the continuous decay of radioactive isotopes in the crust itself. Heat is transferred from the interior towards the surface, mostly by conduction, at an average of 0.065 W/m^2 on continents and 0.101 W/m^2 through the ocean floor. The result is a global terrestrial heat flow rate of around 1400 EJ/y. Considering that continents cover ~30% of the earth's surface and their lower average heat flow, the terrestrial heat flow under continents has been estimated at 315 EJ/y by Stefansson (2005).

As thermal energy is extracted from the active reservoir, it creates locally cooler regions temporarily. Geothermal projects are typically operated at production rates that cause local declines in pressure and/or in temperature over the economic lifetime of the installed facilities. These cooler and lower pressure zones in the reservoir lead to gradients that result in continuous recharge by conduction from hotter rock, and convection and advection of fluid from surrounding regions. Detailed modeling studies (by Pritchett, 1998); and O'Sullivan and Mannington, 2005) have shown that resource exploitation can be economically feasible, and still be renewable on a reasonable timescale, when non-productive recovery periods are considered.

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[1]) 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 ($kW_{electric}$) were generated and in 1913 the first 250$kW_{electric}$ 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 outflow; and
- a hydrothermal reservoir that can be tapped to produce 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 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. 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 called 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 chemical treatment (ex. 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.

Direct Use

Transmission pipelines for the direct use of geothermal energy consist mostly of steel insulated by rock wool (surface pipes) or polyurethane (subsurface). However, several small villages and farming communities have successfully used plastic pipes (polybutylene) with polyurethane insulation, as transmission pipes. The temperature drop is insignificant in large diameter pipes with a high flow rate, as observed in Iceland where geothermal water is transported up to 63 km from the geothermal fields to towns.

It is debatable whether Geothermal Heat Pumps (GHP), also called ground source heat pumps (GSHP), are purely an application of geothermal energy or also partially use stored solar energy. GHP technology is based on the relatively constant ground or groundwater temperature ranging from 4°C to 30°C to provide space heating, cooling and domestic hot water for all types of buildings. Extracting energy during heating periods cools the ground locally. This effect can be minimised by dimensioning the number and depth of probes in order to avoid harmful impacts on the ground. These impacts are also reduced by storing heat underground during cooling periods in the summer months.

There are two main types of GHP systems: closed loop and open loop. In ground-coupled systems a closed loop of plastic pipe is placed into the ground, either horizontally at 1-2 m depth or vertically in a borehole down to 50-250 m depth. A water-antifreeze solution is circulated through the pipe. Heat is collected from the ground in the winter and rejected to the ground in the summer. An open loop system uses groundwater or lake water directly as a heat source in a heat exchanger and then discharges it into another well or into the same water-reservoir (Lund et al., 2003).

Heat pumps operate similarly to vapour compression refrigeration units with heat rejected in the condenser for heating or extracted in the evaporator used for cooling. GHP efficiency is described by a coefficient of performance (COP) which scales the heating or cooling output to the electrical energy input. GHP typically exhibit between 3 and 4 COP (Lund *et al.*, 2003; and Rybach, 2005). The Seasonal Performance Factor (SPF) provides a metric of the overall annual efficiency of a GHP system. It is the ratio of useful heat to the consumed driving energy (both in kWh per year), and it is slightly lower than the COP.

Comparative Advantages of Geothermal Energy Use

Geothermal energy use has several comparative advantages in competitive energy markets.

- 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. This is the weighted average of 85% of the world power plant capacity, according to Bertani and Thain, 2002, and Bloomfield et al., 2003. 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 range from 23-80 g/kWhe for binary plants (based on Frick et al. 2010 and Nill, 2004) and 14-202 g/$kWh_{thermal}$ 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 is74.5% (67,246 $GWh_{electric}$ used from installed capac-

ity of 10.34 $GW_{electric}$ in December 2008 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 27.5% 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 geothermal (ground source) heat pump heating and cooling; 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.
- Displacement of more emissive fossil energy supplies with geothermal energy can also be expected to play a key role in climate change mitigation strategies.

How Big will Geothermal Be? (Communicate!)

The extent or accessibility of geothermal resources will not be a limiting factor for deployment. The key determining factor in the growth in deployment will be the competitiveness of geothermal energy use within local, regional, national and trade zone markets. Earlier estimates for deployment beyond 2010 that were considered in developing forecasts include: IPCC, 2007; IEA, 2008; EREC, 2008, Bertani, 2010. Tables 3 and 4 summarize the conclusions reached by the co-authors in 2010. These forecasts assume improvements in capacity factors power generation from the current average 74.5% to at least 90% by 2050, a level already attained in efficient, existing geothermal electricity generation plants. All direct use estimates for the future (in figure 2) assume an average 31% capacity factor, somewhat higher than the average (27.5%) in 2009.

Table 3. Actual (from 1995 – 2010) and expected (from 2015 – 2100) global long term forecasts of installed capacity for geothermal power from Bertani (2010 and Goldstein, et al, (2011).

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	4.41	1.37	7.57	4.56	12.4 to 53.8	7.5 to 32.4

Table 4. 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 Goldstein, et al, 2011) and forecasts for 2100 based on 1% and 4% average annual growth for 50 years from 2050.

Year	Installed Capacity Actual or Mean Forecast GWe	Electricity Production Actual or Mean Forecast GWh/y	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	75
2015	18.5	121,600	77
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+

Next Steps in Global Resource Assessments

A further global geothermal resource assessment is planned under an existing IEA Geothermal Implementing Agreement research annex. One probabilistic approach could assume a log normal distribution to roughly model the range of recoverable stored heat from a minimum of 0.5% at a 99% probability to a maximum of up to 40% of stored heat at a 1% probability. This implies: a low-side recovery of 1.34% of stored (90% probability); a mid-range recovery of 4.47% of stored heat (50% probability); a Swanson's mean[2] recovery of 6.68% of stored heat; and a high-side recovery of 14.95% of stored heat (10% probability), as in Table 5. This methodology defines quite large potential and does not account for the renewable nature of geothermal energy.

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:

- 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

Table 5. 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 (Goldstein, et al, 2011[1])	139.5	0.1	1.9	6.2	9.8	20.9	55.8
<5 km under continents (Goldstein, et al, 2011[2])	55.9	0.03	0.7	2.5	3.9	8.4	22.4
15°C to 3 km under continents (EPRI, 1978)	42.7	0.02	0.6	1.9	3.0	6.4	17.1

security and climate change mitigation strategies (Bromley, et al., 2010).

- 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
- 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 $GW_{electric}$) 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.
- 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.
- 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.

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

[2] Swanson's mean is the weighted approximation for a log-normal distribution equal to the summation of 30% of the 90% probability value, 30% of the 10% probability value, and 40% of the 50% probability value e.g. (P90 x 0.3) + (P10 x 0.3) + (P50 x 0.4) equals the Swanson's mean value

[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