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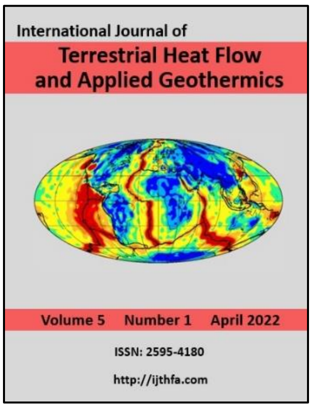

Global Status, Development and Prospects of Shallow and Deep Geothermal Energy

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Abstract

Geothermal heat pump systems (GHP), producing from shallow resources, are the spearhead of geothermal achievement and development. Global heat delivery grew exponentially to 600 PJ in 2020. GHP is the fastest growing segment in geothermal technology and one of the fastest growing application of renewable energy technologies worldwide. Other, various direct-use applications like space heating, bathing and swimming/wellness, industrial, agricultural (especially greenhouses) and aquacultural applications are based on deep, hydrothermal resources. These varieties produced worldwide 420 PJ heat in 2020; the average linear growth was, from 1995 on, about 10 % per year. It can be expected that this trend continues. Power generation, also from deep, hydrothermal resources, develops slowly but steadily, with an average growth-rate of 5 % per year, producing 95.0 TWh in 2020 in 30 countries. When comparing with other renewable power plant technologies (hydro, biomass, solar PV, wind), geothermal falls far behind – both in installed capacity (GWe) and in production (TWh). Only the annual availability of geothermal electricity is the highest among the renewables (60 %). Low geothermal productivity and growth-rate is due to extensive investments for solar PV and wind, which are by orders of magnitude higher than for geothermal power. The technology of Enhanced Geothermal Systems (EGS), based on deep, petrothermal resources, could be a game-changer. Requirements, problems and research goals to find solutions are presented.

1. Introduction

Positive anomalies of terrestrial heat flow can indicate the presence of geothermal resources in the subsurface, heat flow mapping can thus be a pathfinder in geothermal exploration and development. When it comes to geothermal development and utilization, the following main categories need to be considered: Shallow / deep resources, electricity generation / direct use. It is customary to set the boundary between "shallow" and "deep" at 400 – 500 m depth; direct-use means the utilization of the earth's heat for thermal purposes like district heating, greenhouses, spas etc.

There are two main types of deep geothermal resources: hydrothermal and petrothermal. Hydrothermal resources have naturally occurring geothermal fluids at depth, often originating from surface infiltration of precipitation. The fluids can be used as heat carriers and taken out from the ground through boreholes. Such hydrothermal resources like deep aquifers exist only where specific geologic/hydrogeologic conditions prevail (sufficiently porous and permeable rocks), which makes them rather rare. Their fluids can be taken as heat carriers from the ground through boreholes. Petrothermal resources on the other hand, are more or less ubiquitous and immense; they consist basically of the "heat in place" in deep rock formations. The heat must be therefore extracted, e.g. by establishing a fluid circulation through a special, man-made heat exchanger at depth (see below for details). So far, 99.99 % of all existing geothermal power plants use hydrothermal resources.

In the following, the current status of geothermal direct use is presented, from shallow and deep resources. Special emphasis is given to geothermal heat pumps (GHP). Then, today's electricity generation with geothermal power plants is summarized. The development for these is quantified by the annual growth rate. A growth comparison with other renewables electricity generating technologies follows (Hydro, Biomass, Solar PV, Wind). Finally, conclusions and outlook are given.

2. Geothermal Direct-Use

Shallow resources

First, the use of shallow resources will be highlighted. The top 400 meters of the subsurface is warmer in winter and colder in summer than outside air; thus, it provides heating in winter and cooling in summer, with Geothermal heat pump (GHP) systems. These decentral, ground-coupled systems provide space heating, cooling, and domestic warm water production with the same installation. GHPs are nowadays applied in buildings of all kinds, types, sizes and numbers in many countries, for homes, schools, factories, public and commercial buildings. Actually, this technology is one of the fastest growing application of renewable energy technologies worldwide and definitely the fastest growing segment in geothermal technology. Detailed descriptions of the GHP technology and its manifold applications can be found in Rybach (2012, 2022).

Global GHP heat delivery growth is actually exponential (see Figure 1) and provides the majority of geothermal direct-use, This majority developed from 13.0 % of all geothermal direct-uses in 1995 to 58.8 % in 2020.

Deep resources

In other direct-uses, hot fluids deeper from the ground can be used for numerous applications like space heating, bathing and swimming/wellness, industrial, agricultural (especially greenhouses) and aqua-cultural uses. Their current contributions (along with the shallow GHPs) are displayed in Figure 2.

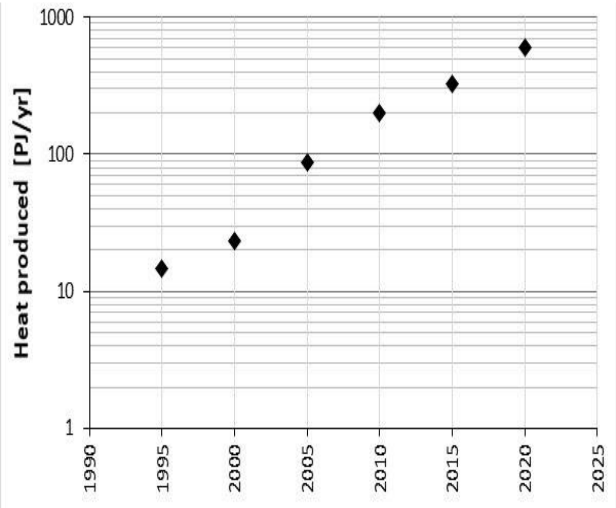

Figure 1 - Global heat delivery of GHP systems in 2020. Data from Lund and Toth (2020) are plotted.

A common direct-use type of deep, hydrothermal resources is geothermal district heating. It is now widespread and often significant: For example, over 90 % of all buildings are heated in Iceland by geothermal fluids, often transported over long distances. In and around Paris/France, over 200’000 apartments are connected to district heating networks. Usually, the plants use two wells (production/reinjection – a so-called “doublet”)

In Bavaria/Germany, especially in the Munich area there are now over 20 installations operating. The combined heat & power (cogeneration) uses deep resources. This is now becoming increasingly popular in Germany, like at Grünwald/Laufzorn (power plant 4.3 MWe, production 18.2 GWe in 2019, heating plant 40 MWth, delivery 56,3 GWh in 2019). Such plants generate mainly power in summer and provide heating in summer. An impressing number of German cogeneration installations is assembled in the German GeoTIS Information System, downloadable from Geothermische Standorte (geotis.de); details about the German deep geothermal installations (also those without cogeneration) can be found in Agemar et al. (2014).

In total, the global geothermal direct-use from deep resources provided in 2020 420 PJ heat, with and installed capacity of 107,7 GWth. Shallow and deep geothermal direct use was applied 2020 in 88 countries (Lund and Toth, 2020).

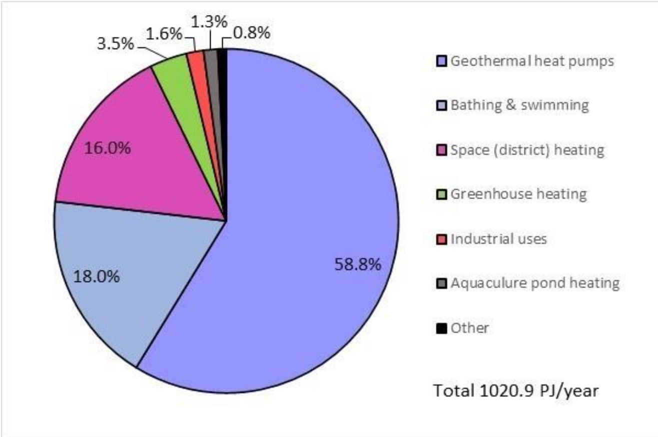

Figure 2 - Various global direct uses in 2020. Data from Lund and Toth (2020) plotted.

3. Geothermal power generation

Geothermal power plants use deep resources and provide base-load electricity. Currently (in 2020), the total globally installed capacity amounted to about 15.9 GWe, in 30 countries, with a total production of 95.0 TWh/yr (Huttrer, 2020). So far, practically all power plants use hydrothermal resources. Geothermal power generation started in 1904 in Larderello, Italy. In earlier days, reservoirs with dry steam have been tapped, later also those with steam/water mixtures. Such high-temperature fields (>200°C in less than 2 km depth) are mostly located in volcanic areas and are correspondingly rare. The average power plant size is about 50 MWe. The largest hydrothermal plant to date, at Nga Awa Purua/New Zealand operates with a single 140 MWe turbine unit and is fed by only 6 production wells (Rybach, 2014).

With advanced technology (=binary power plants) it is now possible to convert heat to power also with lower fluid temperatures (100 – 120°C). But the conversion efficiency is correspondingly low (a few percentage points only) and the plant size is also limited (only a few MWe).

Many more details about the technology of geothermal power plants can be found in Di Pippo (2015).

4. Development trends, Prospects

Direct-use, Shallow Resources

Most of the GHP systems operate with closed-system borehole heat exchangers (BHE). Besides these, groundwater-based GHP systems are operating in numerous countries but in smaller numbers: In groundwater protection areas their operation is restricted or forbidden – since their system is not closed. Technical details of groundwater based GHPs are also described in Rybach (2012, 2022). The impressing global GHP development in the years 1995-2020, as shown in Figure 1, includes also groundwater-based GHPs. The number of countries using GHPs is also increasing (details in Lund and Toth, 2020).

GHP growth was so far exponential (see Figure 1), with impressive growth rates: From 1995 to 2010, 17.4 % per year, from 2010 to 2020 11.0 % per year. The continuation of the trend is expected to remain around the lower rate.

Direct-use, Deep Resources

As already mentioned, hydrothermal resources are used for various applications, like district heating, bathing and swimming/wellness, industrial, agricultural (especially greenhouses) and aqua-cultural uses. Their heat delivery growth from 1995 on is depicted in Figure 3. The growth is significant and steady; Whether the increase in the last couple of years can be sustained is not yet clear. Lately, the increase of district heating was substantial in Turkey and Germany, and the greenhouse heating in The Netherlands (details in Lund and Toth, 2010). The direct-use for deep resources grew, from 1995 to 2020 regularly in a rather linear manner with an average annual growth rate of about 10 %. This trend will most probably continue.

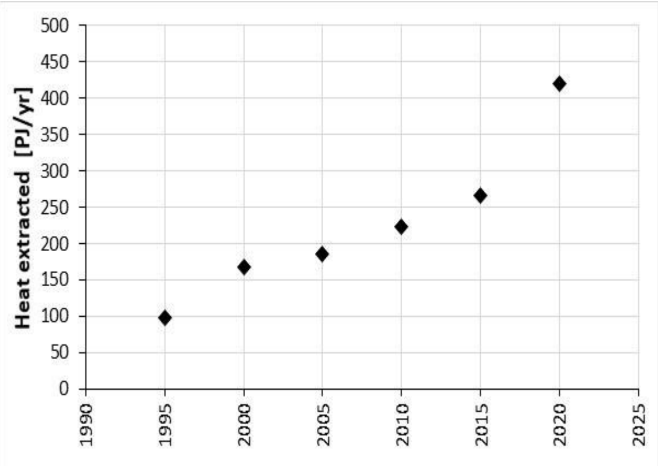

Figure 3 – Growth of direct-use heat delivery 1995 – 2020 from deep resources. Data from Lund and Toth (2020) plotted.

Power generation

The number of countries with geothermal power plants grew from 20 in 1995 to 88 in 2020 (Huttrer, 1995, 2020). The annual growth, in terms of globally installed capacity amounts to about 5 % per year since several years. The growth is shown in Figure 4. The growth is highly different from country to country; the leader is Turkey: From 20.6 GWe in 1995 (Huttrer, 1995) over 82 GWe in 2010 (Bertani, 2010) to 1,549 GWe in 2020 (Huttrer, 2020).

The growth of geothermal power plants world-wide is steady, but much slower than of other renewable energy technologies. These differences are presented and discussed below.

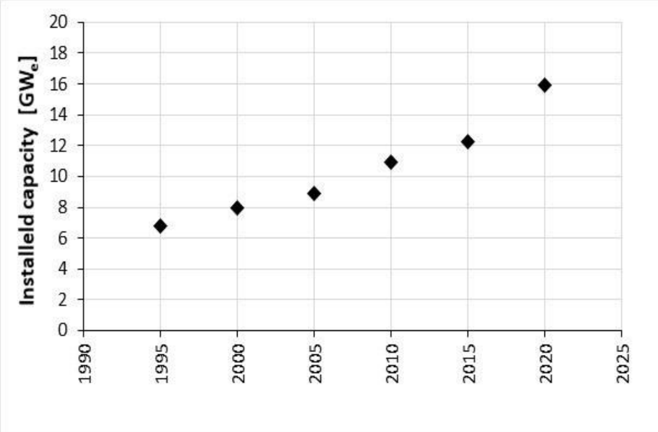

Figure 4 – Growth of globally installed capacity of geothermal power plants 1990 – 2020. Data from Huttrer (2020) plotted.

5. Comparison of power generation growth with different renewable technologies

All over the world, there are many electric power plants that use quite different technologies: Hydrothermal, Biomass, Solar PV, Wind, Geothermal. Their development over the years is also quite different. There are also differences in their performance: Whereas power plants can be regulated (hydropower) or provide base-load electricity (geothermal), the production of the others like solar PV and wind depend on daytime, season or weather conditions.

An interesting comparison of growth tendencies among the Renewables can be found in Kurtz (2019). Figure 5 shows the growth of power plant capacities of fossil, nuclear, solar, wind and geothermal technologies, on logarithmic scale, over the years 1980 to 2015. The differences are striking, especially the remarkable growth of wind and solar PV.

It is also interesting to see differences in global output of the renewable power plants worldwide: These are assembled for the different renewable technologies in Table 1, based on data from the REN21 2021 Global Status Report. The geothermal production is clearly the lowest but on the other hand, geothermal production availability is the highest.

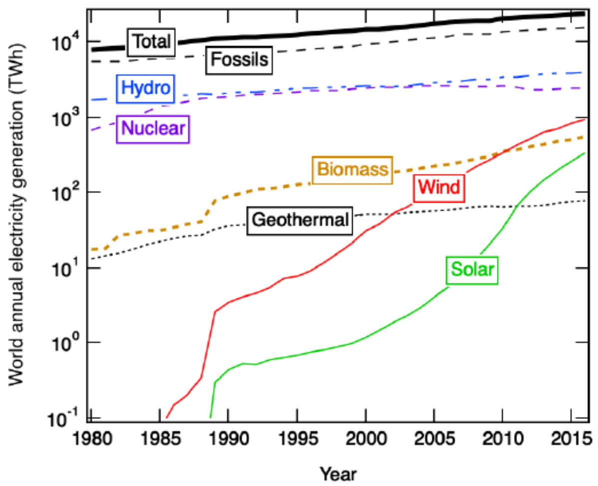

Figure 5 - Growth of global annual electricity generation by technology types. From Kurtz (2019).

The annual growth of geothermal power, in terms of installed capacity amounts to about 5 % per year since several years. The numbers are similar for hydropower and biomass generation. Geothermal power (in terms of globally installed capacity) was well ahead of solar PV until about 2007; nowadays, wind and solar PV exhibit two-digit, exponential growth with 30-40 % annually. In terms of electricity production, solar PV overtook geothermal power for the first time in 2011 and increased since then the gap strongly. More details see in Rybach (2014).

Table 1 - Comparison of global electricity production by renewable technologies in 2020 (data from REN21, 2020). (Star symbol refers to data from Huttrer, 2020).

Technology	Installed capacity		Annual production		Annual Availability
	GWe	%	TWh/yr	%	%
Hydropower	1,170	41.3	4,370	59.3	43
Biomass	145	5.1	602	8.2	47
Wind	743	26.2	1,370	18.6	21
Geothermal	**15.9***	**0.6**	**95***	**1.3**	**68**
Solar PV	760	26.8	930	12.6	14
Total	**2,834**	**100**	**7,367**	**100**	-

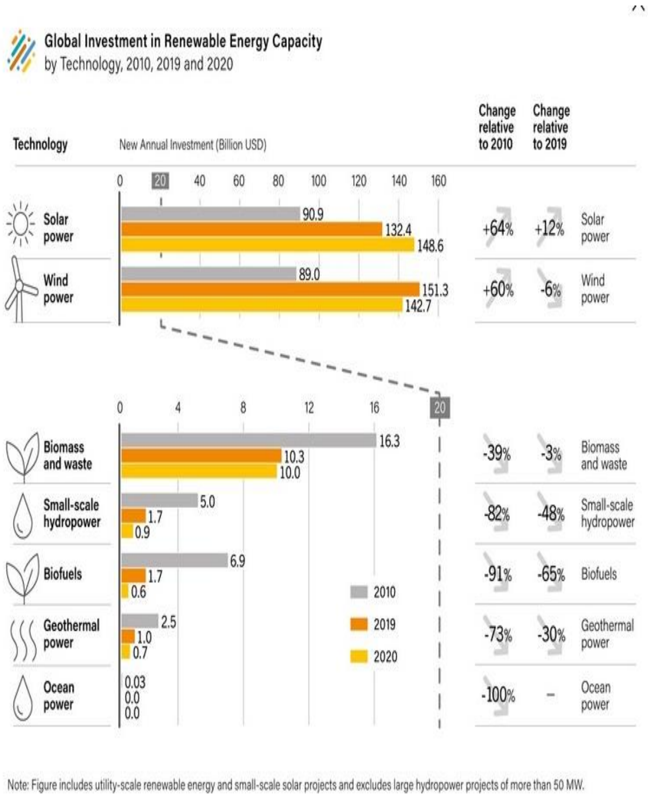

Figure 6 - Global investment in various renewable technologies for electricity generation 2010 – 2020 (From REN21, 2021).

No wonder that geothermal power lags badly behind solar PV and wind – the global market share and investments in solar and wind power are by orders of magnitude higher than those of geothermal, see Figure 6.

From the above comparison figure and table, it is evident that geothermal power development is currently left far behind by wind and solar PV: whereas geothermal development growth is more or less linear (steady but slow growth – increasing just a few percent per year), wind and solar PV exhibit accelerating growth with a clearly exponential tendency. To keep pace, geothermal power growth needs to be accelerated.

But how to achieve this acceleration? Until today, the growth in installed geothermal power capacity originated entirely from "conventional", hydrothermal resources. Such resources are found in numerous but special places, with high-temperature geothermal fluids present in the subsurface at relatively shallow depths (2 – 4 km) in useful quantities. Such special places can mainly be found in volcanic terranes or in other regions, depending on their plate tectonic and sedimentary settings (details see e.g. in Fridleifsson et al, 2008). It can be expected that geothermal power development based on conventional high-enthalpy resources will remain more-or-less linear in the future, thus some new technology is needed to provide the exponential growth component. In the following, the case is made that EGS technology (Enhanced Geothermal Systems) could play this role.

6. EGS technology: Goals and open questions

The renowned M.I.T. study "The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21th Century (Tester et al., 2006) suggests that Enhanced Geothermal Systems will be the future of geothermal energy utilization. Enhanced Geothermal Systems is an umbrella term for various other denotations such as Hot Dry Rock, Hot Wet Rock, Hot Fractured Rock. The M.I.T. study determined EGS resources > 200,000 EJ alone for the USA, corresponding to 2,000 times the annual primary energy demand.

The EGS principle is simple: In the deep subsurface where temperatures are high enough for power generation (150-200 °C) an extended, well distributed fracture network is created and/or enlarged to act as new fluid pathways and at the same time as a heat exchanger ("reservoir"). Water from the surface is pumped through this deep reservoir using injection wells and recovered by production wells as steam/hot water. The extracted heat can be used for district heating and/or for power generation. Figure 7 shows the schematics of such a system.

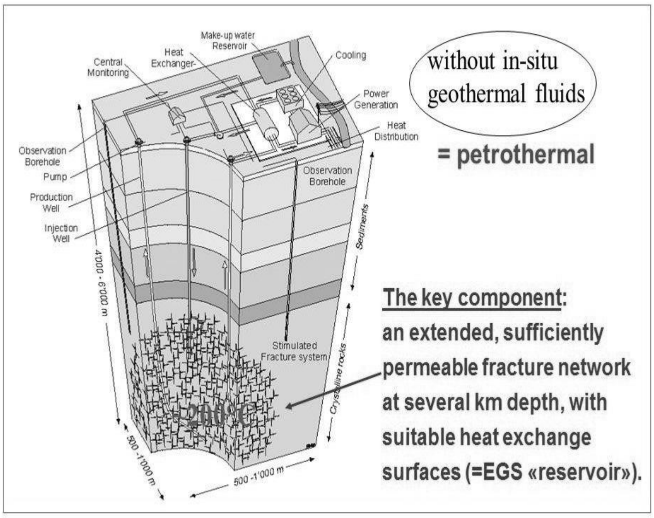

Figure 7 - Schematics of an EGS installation for power generation and district heating. From Häring Geothermal Explorers Ltd. 2007, with additions.

The core piece of an EGS installation is the heat exchanger at depth. It is generally accepted that it must have a number of properties in order to be technically feasible and economically viable. These refer to the total volume, the total heat exchange surface, the flow impedance, and the thermal and stress-field properties. The key properties are summarized in Table 2.

Table 2 - Requirements for a technically feasible and economically viable, standard EGS heat exchanger (for a target 5 MWe / module). From EGEC (2012).

Life of the system	~ 20 years
Temperature of the wells	~ 200 °C
Separation between wells	~ 600 m
Production flow rate	~ 75 kg s^{-1}
Flow impedance	~ 0.1 MPa l^{-1} s
Water loss	~ 10 % max.
Thermal drawdown	~ 10 %
Contact surface area	~ 10 million m^2
Reservoir rock volume	~ 300 million m^3
Interest rate for capital support	~ 5%, no levy support

Although the minimum requirements for an economically viable EGS reservoir are herewith set, their realization in a custom-made manner to comply with differing site conditions is not yet demonstrated. The key issue is the development of a technology to produce electricity and/or heat from a basically ubiquitous resource, in a manner relatively independent of local subsurface conditions, i.e. to develop a technology for the creation of EGS downhole heat exchangers –wherever needed– with the properties quantified above. To realize these, EGS is still at the proof of concept phase.

Therefore, several questions about establishing and operating EGS heat exchangers that are still open need to be addressed and answered. Here are some of the key issues:

- Development of a technology to produce electricity and/or heat from a basically ubiquitous resource, in a manner +/- independent of site conditions;
- Site exploration must clarify the local temperature and stress field, lithology, kind and degree of already existing fracturing, natural seismicity;
- In creating EGS heat exchangers at several kilometers depth, questions of rock mechanics like the role of anisotropy degree, stress change propagation/ transmission –fast / dry "? slow / „wet "? (under different site conditions)– need to be answered;
- EGS induced seismicity (during stimulation in establishing the EGS heat exchanger but also during production) becomes a real issue, and thus needs to be controlled. Magnitudes need to be limited since public acceptance will be decisive (Majer et al 2007, Giardini, 2009).
- Uniform connectivity throughout a planned reservoir cannot be engineered so far. There is no experience with possible changes of an EGS heat exchanger over time; permeability enhancement (e.g. new fractures generated by cooling cracks) could increase the recovery factor while permeability reduction (e.g. by mineral reactions) or short-circuiting could reduce recovery.
- This leads to the question of production sustainability. The production level needs to be set in order to guarantee longevity of the system (details in Rybach and Mongillo, 2006).
- It will be decisive to see whether and how the EGS power plant size could be upscaled, at least to several tens of MWe.

EGS chances and challenges, problems and possible solution have already been presented in 2010, at the World Geothermal Congress in Nusa Dua, Bali/Indonesia (Rybach, 2010). More EGS research needs and suggestions can be found in Rybach and Kohl (2018).

One thing is certain: The heat is down there, in immense amounts; we just have to learn how to get it out. Only very intensive, focused research and development, resulting in pilot and demonstration facilities could bring EGS ahead. This will need very substantial funding, which could arise from public-private partnership.

7. Conclusions, outlook

Nowadays, shallow geothermal resources are well harvested by Geothermal Heat Pump systems worldwide. This technology is one of fastest growing application of renewable energy technologies worldwide and definitely the fastest growing segment in geothermal technology. Their global growth rates are spectacular, exponential.

Deep hydrothermal resources are utilized for various direct-use applications, like district heating, bathing and swimming/wellness, industrial, agricultural (especially greenhouses) and aquacultural uses. Growth rates are linear, steady,

Hydrothermal resources of deep geothermal energy prevail only in specific geologic settings and are therefore correspondingly rare. Petrothermal resources (i.e. the heat in place in deep rock formations) on the other hand are immense and more or less ubiquitous. So far, practically all deep geothermal installations (power plants, direct-use installations) utilize hydrothermal resources.

Deep Geothermal energy utilization, for power generation from hydrothermal resources, develops steadily world-wide, albeit with modest, linear growth rates. In some countries, like in Turkey, the growth is remarkable. At the same time, wind and solar PV develop exponentially, with 10 – 30 % annual growth. In other words: Globally, geothermal power falls back badly behind wind and solar PV.

Therefore, geothermal growth should be accelerated. Since the development of hydrothermal resources cannot be hastened –mainly because such resources are limited– the only option that remains are petrothermal resources. The only problem: How to get out the heat in place? In particular, the following questions need to be addressed:

- Where? (favorable site conditions → exploration)
- How? (sufficient, deep heat exchanger realization → proper, site-dependent stimulation)
- With what efficiency? (recovery factor → enhancement, production sustainability) *Recovery factor, R (%) = extractable heat/heat in place*

- How to handle possible risks of EGS realization/operation like induced seismicity?

These open questions need to be answered – and rather quickly so. In addition, upscaling EGS power plant size will be decisive. EGS pilot plants are badly needed, as is long-term experience. Personally, I can imagine that the future of geothermal energy lies in EGS!

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