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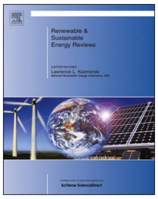

Comparison of geothermal with solar and wind power generation systems

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ABSTRACT

Geothermal, solar and wind are all clean, renewable energies with a huge amount of resources and a great potential of electricity generation. Geothermal energy had definitely dominated the renewable energy market in terms of the installed electricity power about 30 years ago. The unfortunate fact is that the total installed capacity of geothermal electricity has been eclipsed by solar and wind in recent years. In this paper, benefits of using renewable energy resources (RER) have been summarized and attempt has been made to explain the recent trends causing the shift from geothermal energy to solar and wind. Cost, payback time, size of power generation, construction time, resource capacity, characteristics of resource, and other factors were to compare geothermal, solar, and wind power generation systems. Furthermore, historical data from geothermal, solar, and wind industries were collected and analyzed at the global scale. The data from hydropower were also considered in the comparison. Finally, we proposed suggestions for the geothermal industry to catch up with solar and wind industries.

Contents

1. Introduction

The overdevelopment and consumption of fossil energy resources (FER) have caused environmental and ecological problems that impacts our daily lives. Continued dependency on fossil fuels may increase the rate of global warming with disastrous consequences [1]. When the Intergovernmental Panel on Climate Change (IPCC) issued its 2007 assessment [2], it recommended to keep atmospheric greenhouse gases below 450 ppm in order to keep the temperature rise under a 2 °C target [3]. It seems that this is a big challenge. In the coming decades, global environmental issues will significantly affect patterns of energy use around the world. Any future efforts to limit carbon emissions are likely to alter the composition of total energy-related carbon emissions by energy sources. Air pollution is becoming an important environmental concern in some of the developing countries. In this regard, renewable and clean energy resources (RCER) are becoming attractive for sustainable energy development and environmental pollution mitigation in these countries [4–12].

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Not only do future energy technologies need to be clean and renewable, but they also need to be robust, especially in some developing countries such as China [13,14]. The recent heavy fog enveloping a large swathe of Eastern and Central China is a stark example. There was neither sunshine (no solar energy) nor wind (no wind turbine rotating). Furthermore, Beijing was hit 4 times by heavy haze and fog within one month in January 2013. Hundreds of flights were cancelled and highways were closed. The Beijing meteorological observatory issued a yellow alert (the highest level alert) for heavy fog on January 22, 2013.

The existing energy systems in many countries are not sustainable due to the increasing energy demand triggered by population expansion and economic growth, as well as short-and long-term uncertainty in connection with the availability of resources. A new energy structure with consumption-rationing and high efficiency needs to be achieved simultaneously. More emphasis on the use of renewable and clean energy sources is important to shift the structure of our energy system towards sustainability [15].

Ming et al. [16] analyzed the physical and technical potential of several disrupting technologies that could combat climate change by enhancing outgoing long wave radiation and cooling down the Earth. The technologies proposed were power-generating systems that were able to transfer heat from the Earth's surface to the upper layers of the troposphere and ultimately to space. The economic potential of these technologies is clear, as they simultaneously produce renewable energy (RE), thus reducing future greenhouse gases emissions, and also are more socially acceptable compared to geoengineering.

One of the currently practical solutions to the problems caused by FER may be the large scale utilization of RE. In recent decade or so, RER have grown fast, especially the solar and wind energies although the utilization of RE is still far from its potential at a global scale [17]. The relatively fast growth of using RER might be because of their many benefits: (1) reducing the emission of CO_2 as well as other greenhouse gases and improving environment; (2) assisting with energy independence in many countries without enough fossil energy resources; (3) diversifying resources of energy production and improving the structure of the existing energetic systems; (4) contributing to a sustainable development; (5) increasing local labor employment; (6) reducing risks and disasters (for example, explosions of natural gas pipes) caused by using FER.

As summarized in Renewables 2014: Global Status Report [17], hydropower rose by 4% to approximately 1000 gigawatts (GW), while other renewables collectively grew nearly 17% to an estimated 560 GW. Globally, hydropower and solar photovoltaics (PV) each accounted for about one-third of renewable power capacity added in 2013, followed closely by wind power (29%). For the first time, more solar PV than wind power capacity was added worldwide. By the end of 2013, renewables comprised an estimated 26.4% of the world's power generating capacity. Unfortunately, the contribution of geothermal power (GP) is very small.

It is known that geothermal energy has many advantages over solar and wind systems. These advantages include: (1) unaffected by weather; (2) it is a base-load power; (3) it is stable and has high capacity factor over 90% in many cases; (4) it requires less land and has less ecological effect; (5) it has high thermal efficiency. The total installed capacity of geothermal electricity, however, is much less than those of solar and wind energies.

Geothermal energy has two types of utilizations: direct use and power (electricity) generation. Direct use includes space heating (for example, greenhouse heating, snow melting, plant and food heating), cooling, and other applications using low enthalpy geothermal energy. Despite the direct use, including the use of geothermal heat pumps, of geothermal energy has developed rapidly during the past many years [18–23], only the geothermal power generation has been considered to compare with hydropower, solar and wind energies in this paper.

Trying to find the reason for the stagnant growth in geothermal power generation, Kubota et al. [15] conducted semi-structured interviews with 26 stakeholders including developers, hot spring inn managers, and local government officials. The results showed that the societal acceptance of geothermal power by local stakeholders was the fundamental barrier as it affected almost all other barriers, such as financial, technical, and political risks. They thought that a key reason for opposition was identified as uncertainty about the reversibility and predictability of the adverse effects on hot springs and other underground structures by geothermal power production and reinjection of hot water from reservoirs.

Evan et al. [24] has assessed the non-combustion based renewable electricity generation technologies against a range of sustainability indicators and using data obtained from the literature. The cost of electricity, greenhouse gas emissions and the efficiency of electricity generation were found to have a very wide range for each technology, mainly due to variations in technological options as well as geographical dependence of each renewable energy source. The social impacts were assessed qualitatively based on the major individual impacts discussed in literature. It was found that wind power is the most sustainable, followed by hydropower, photovoltaic and then geothermal. Dombi et al. [25] assessed the sustainability of renewable power and heat generation technologies, ten technologies of power generation were examined in a multi-criteria sustainability assessment frame of seven attributes which were evaluated on the basis of a choice experiment survey. The results demonstrated that concentrated solar power (CSP), hydropower and geothermal power plants were favorable technologies for power generation.

As analyzed by Resch et al. [26], the theoretical and technical potentials of RER are huge compared to the status quo of energy consumption in general and the current deployment of RER, respectively. From a theoretical perspective RER could contribute to meet more than 300,000 times the current overall primary energy demand at global scale. They also pointed out, by considering technical constraints still the potential remains 16 times higher than current needs, but at present (2008) RER cover approximately only 13.1%. De Vries et al. [27] investigated the RER potential for the first-half of the 21st century at a global level. Unfortunately geothermal energy was not considered. Only wind, solar-PV and biomass were included.

Haas et al. [28,29] elaborated on historically implemented promotion strategies of renewable energy sources and the associated deployment within the European electricity market in 2010. They found that it was not all about the common question of feed-in tariffs vs. quota systems based on tradable green certificates, but more about the design criteria of implemented RES-E support schemes. Alemán-Nava et al. [30] analyzed renewable energy research progress in Mexico. The results showed that hydropower is the renewable energy source with the highest installed capacity within the country (11,603 MW), while geothermal power capacity (958 MW) makes Mexico ranked 4th in the use of this energy worldwide.

However, the growth of geothermal power generation in many other countries is very slow. As reported by Wang, et al. [31], the sedimentary basin geothermal resources in major plains (basins) in China are 2.5×10^{22} J, which is equivalent to 853.19 billion tons of standard coal. The geothermal resource in 3.0–10.0 km deep enhanced geothermal system (EGS) of mainland China is about 2.5×10^{25} J in total, which is equivalent to 860×10^6 million tons of standard coal. Even though only 2% is explored, the energy is equivalent to 5300 times as much as the total annual energy consumption in China in 2010. However, the currently installed

Table 1a
Comparison of global resources, installed power and increase in last five years (2008–2013) [17,32–37].

Energy	Resource [32] (TW)	Resource [33] (TW)	Installed (GW)	Increase (GW)	% of Total power installed (%)
PV	49.9	6500	139	116	2.42
Wind	20.3	1700	318	159	5.55
Hydro	1.6	15,955	1000	125	17.44
Geothermal	158.5	67	12.0	1.10	0.21

Table 1b
Comparison of the installed power and increase in last five years (2009–2013) in Iceland [17,38].

Energy	Installed (GW)	Increase (GW)	% of Total power installed
PV	~0	~0	~0
Wind	~0	~0	~0
Hydro	1.633	0.33	70
Geothermal	0.7	0.12	30

Table 1c
Comparison of the installed power and increase in last five years (2008–2013) in China [17,38–42].

Energy	Installed (GW)	Increase (GW)	% of Total power installed (%)
PV	19.9	19.5	1.60
Wind	91.4	71.5	7.33
Hydro	260	63	20.84
Geothermal	0.028	~0	0.0022

Table 1d
Comparison of the installed power and increase in last five years (2008–2013) in The United States [17,38–42].

Energy	Installed (GW)	Increase (GW)	% of Total power installed (%)
PV	12.1	10.9	1.14
Wind	61.1	26	5.76
Hydro	78.4	7.3	7.39
Geothermal	3.4	0.2	0.32

geothermal power is about 28 MW in China and does not increase much over the past 30 years. On the other hand, the installed power of PV and wind are 19.9 GW and 91.4 GW (see Table 1c), respectively, which are far more than geothermal energy.

One can see from the above brief literature review that geothermal energy resource (GER) has many advantages compared to other modern RER (solar and wind energies) but the installed power capacity for GER is far less than solar and wind energies. Unfortunately there have been few papers in which the essential reasons for this stagnant growth rate of GP at both country (few countries are exceptional) and global scales. In this study, cost, payback time, capacity factor, size of power generation, construction time, resource capacity, characteristics of resource, social impact, and other factors were compared for geothermal, solar, and wind power generation systems. Historical data from geothermal, solar, and wind industries were collected [17,32–42] and analyzed in order to find the reasons why geothermal power generation falls so far behind solar and wind energies. Possible directions have been proposed to speed up the growth rate of geothermal power generation. Note that only geothermal electricity generation was considered and direct use of geothermal energy was not included in this paper.

2. Comparison of resources, installed power and capacity increase

The resources, installed capacity, and its increase in the last five years for PV, wind, hydro and geothermal energies of the world are listed in Table 1a. Note that the resources of the four energy types from different references are very different. The data from World Energy Assessment (WEA) report [32] will be used later on in this paper. According to WEA report [32], geothermal energy has the largest resources among the four types of renewable energies. However, the total geothermal power installed in world was about 12.0 GW until May 2013 [17], much less than those of solar and wind energies. Another important issue is that the increase of the installed power from GER in last five years is also very slow.

Also listed in Table 1a are the values of the percentage of each RE to the total power (including renewable and traditional energy resources) installed in the world. Note that the total installed power in all of the countries until 2013 was 5733.2 GW [42]. One can see that the percentage of GP to the total power installed in the world is very small and less than 1%. On the other hand, the percentage of solar, wind, and hydropower RE to the total installed power are 2.42, 5.55, and 17.44%, respectively, which can play an important role in the international power market.

In order to look at the situations in different countries, Iceland, China, and the United States (US) were chosen for the analysis. The installed capacity and its increase in the last five years for those energies in three typical countries are listed in Tables 1b–1d, respectively. The resource data are not included Tables 1b–1d because the numbers are very different from different sources. Interestingly the power in Iceland is almost all from RE. Obviously this is not the case in China and US.

Also listed in Tables 1b–1d are the percentages of each RE over the total installed power of each country. The ratio of GP to the total installed power was about 30% in Iceland, but only 0.0022% in China and less than 1% in US. Note that the total installed power in China and US until 2013 is 1247.4 and 1061.0 GW, respectively [42]. The reasons for the imbalance of developing GP among different countries are complex and will not be analyzed in detail because this is not the main purpose of this paper. However, a brief discussion will be presented in the following section.

According to Table 1c, the solar PV and wind energies are developing very fast in China. The increase in the installed power are 19.5 and 71.5 GW for solar PV and wind energies, respectively. In the US (see Table 1d), the solar PV and wind energies are developing fast too. The increase in the installed power are 10.9 and 26 GW for solar PV and wind energies, respectively. The growth rates of solar PV and win in the two countries are much greater than that of geothermal.

It is known that the resources of solar PV, wind and geothermal energies (SWGE) depend on the surface radiation from the sun, wind speed above the ground, and heat flow rate related to the temperature of geothermal reservoirs in deep, individually. Because of the above reason, these parameters are discussed in following.

The modeled solar downward radiation in the world is shown in Fig. 1. The global average radiation was about 193 W/m^2 and that over land was around 185 W/m^2. The resource of all PV worldwide was about 6500 TW and that over land in high-solar locations was about 340 TW, as reported by Jacobson [33].

Fig. 2 shows the modeled world wind speeds at 100 m. The resource of all wind worldwide was about 1700 TW and that over land in high-wind areas outside Antarctica was about 70–170 TW reported by Jacobson [33]. Note that the predicted world power demand in 2030 would be 16.9 TW.

Fig. 3 shows the distribution of world average heat flow rate (Fig. 3a) and the location of world geothermal power plants

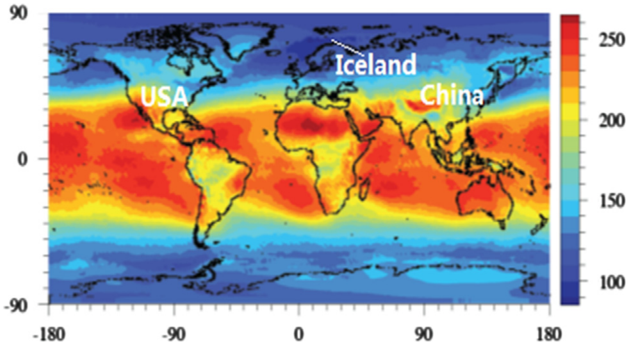

Fig. 1. Modeled world surface radiation (W/m^2). Global average: 193; land: 185 [33].

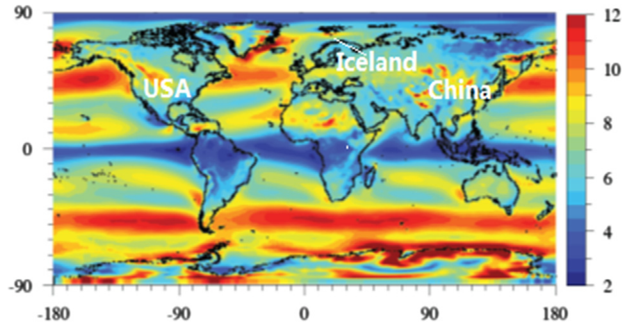

Fig. 2. Modeled world Wind speeds at 100 m [33].

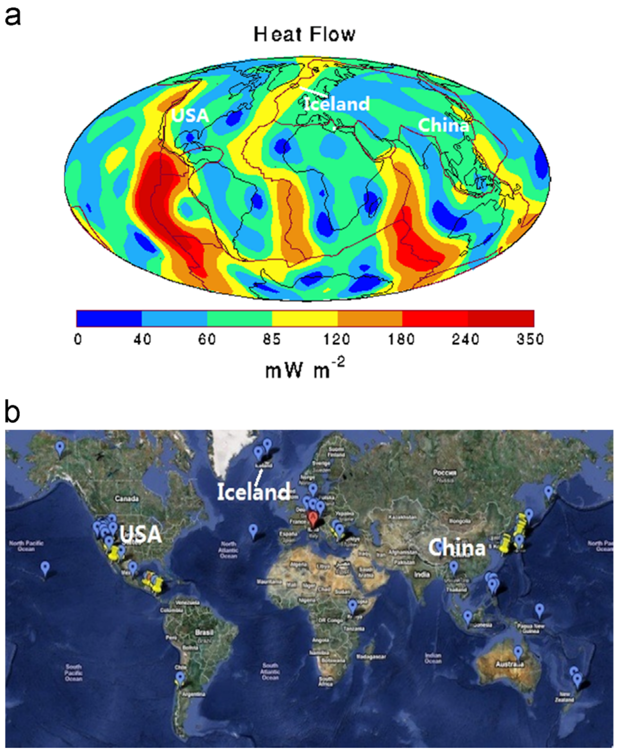

Fig. 3. (a) Distribution of world heat flow rate.
Source: ⟨http://geophysics.ou.edu/geomechanics/notes/heatflow/global_heat_flow.htm⟩ average: 0.06 W/m^2, (b) Location of world geothermal power plants.
Source: thinkgeoenergy.com.

(Fig. 3b). One can see that the two maps (Fig. 3a and b) match very well, that is, the areas with the highest heat flow rates have the most geothermal power plants. The geothermal resource worldwide was about 67 TW [37].

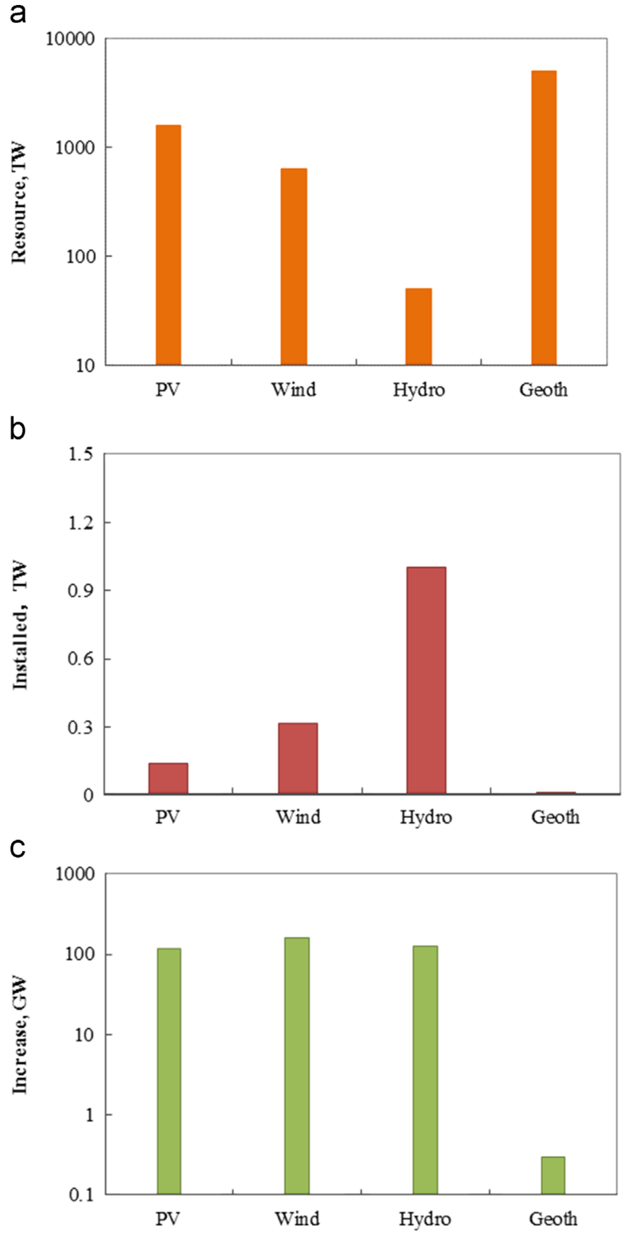

Fig. 4. Resources, installed capacity and the increase in the last five years. (a) Resource (WEA) [32], (b) installed power, (c) power increase in last five years.

As stated previously, the reasons for the imbalance of developing GP among different countries are complex. However, one of the obvious issues is the heat flow rate related to the temperature of geothermal reservoirs in deep. Iceland has a very high heat flow rate but China has a very low value, as shown in Fig. 3. Note that China has great solar surface radiation and high wind speed, which might be one of the reasons, in terms of resource conditions, that the installed solar and wind power in China could grow fast (see Table 1c).

In order to observe the differences among RE more clearly, the data to show the resources, installed capacity and the increase of power in the last five years at global level are shown in Fig. 4a–c. One can see that hydropower has the smallest resource but has the greatest installed power at global level. GP has the greatest resource but has the smallest installed power and power increase in the last five years.

The change of the installed global power capacity with time for geothermal, PV, and wind is shown in Fig. 5. One can see that PV's

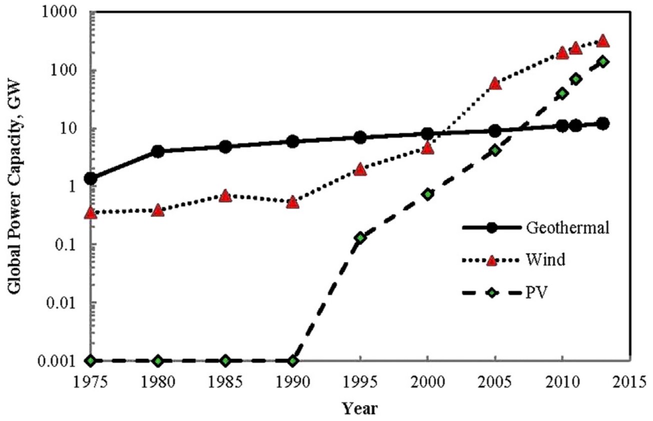

Fig. 5. Comparison of installed global power capacity for individual energy types.

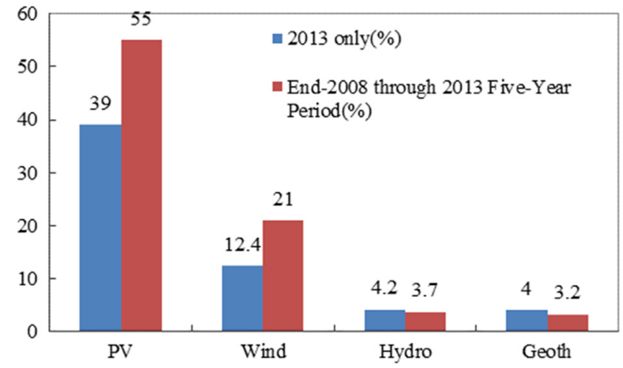

Fig. 6. Average annual growth rates of renewable energy capacity, 2008–2013. *Source*: [17].

power growth rate was the maximum, followed by wind power in recent two decades although the installed power of PV and wind were kept almost unchanged before 1990. Another interesting observation is that the growth of the installed power of solar PV and wind was exponential in the last 20 years but the growth of geothermal was nearly linear with a small slope that implies a small increasing rate.

Fig. 6 demonstrates the average annual growth rates of renewable power capacity only in 2013 and in the last five years during the period of 2008–2013.

The average annual growth rate of geothermal power was only about 3.2% while those of PV, wind, and hydropower were about 55, 21, and 3.7% respectively during the same period of the last five years. Remarkably the installed power of PV in one year (2013) increased about 39%.

3. Comparison of cost, efficiency, and environmental impacts

The cost, payback time, and construction time for different energy types are listed in Table 2. The data are also plotted in Fig. 7. The data of coal and gas power systems were used for reference and convenience to make the comparison. The cost of geothermal energy is very close to wind energy but much less than PV. Compared with wind and PV, the main disadvantages of geothermal energy may be the long payback time and the construction period (Tc). According to Barbier [43], geothermal prices are heavily increased by the long project development times, high costs and risk of exploratory drilling. And drilling can account for up to 50% of the total project cost [44].

Table 2
Comparison of cost, payback time, and construction period [35].

	Cost (US/kW h)	Payback (year)	Construction (year)
PV	$0.24	1–2.7	0.3–0.5
Wind	$0.07	0.4–1.4	< 1
Hydro	$0.05	11.8 (small)	1
		0.5 (large)	10–20
Geothermal	$0.07	5.7	3–5
Coal	$0.04	3.18	1–3
Gas	$0.05	7	2–3

In addition to cost, parameters like capacity factor (CF), efficiency, and environmental impacts for individual energy generation technology are also important factors that affect the growth. These parameters are listed in Table 3 and plotted in Fig. 8.

Geothermal power has the highest capacity factor, over 90% in many cases, as listed in Table 3. The average value of the capacity factor of PV is about 14% and that of wind is around 25%. Considering this, the energy generated per year may be more important than the power installed. The amount of energy generated per year was calculated using the power installed listed in Table 1 and the capacity factor from Table 3 and the results are plotted in Fig. 9. The energy generated by geothermal was close to PV after considering the capacity factor.

Compared with wind, hydro and PV power, the average emissions from geothermal are higher, as listed in Table 3. Most modern plants, however, either capture the CO_2 and produce dry ice, or reinject it back into the reservoirs [45].

Table 3 shows that the renewable energies all have the problem of significant footprint (Figs. 10–12), occupying a large amount of land. Geothermal power plants have relatively small surface footprints, which is in the range 18–74 km^2/TW h, with major elements located underground [46]. Gagnon et al. [47] reported a total footprint of 72 km^2/TW h for wind power, without allocating any share of this to agriculture. Lackner and Sachs [48] find a land occupation of 28–64 km^2/TW h for PV power with no dual purpose allocation. A generic land requirement was estimated as 750 km^2/TW h per year [49].

Geothermal power has the largest consumption of water because of the need of cooling. However, the water consumption by geothermal power could be reduced remarkably by using new cooling technologies. Also, water consumption can be controlled by the total reinjection of polluted and foul smelling wastewater, non-evaporative cooling, general pressure management and closed-loop recirculating cycles [50].

4. Comparison of social impacts and government barriers

Social impact of renewable energies is also an important factor to affect the growth rates. Table 4 lists the social impacts [24] and the government barriers (mostly the infrastructure system). Relatively, PV and wind have minor social impacts. The main social impact of geothermal may be seismic events, which could be very serious in some cases [51]. Except hydro-power, the other renewable energies may all face the problem of integrating and improving the grid and other infrastructure systems.

5. Unit power size and modularization

Do the size of a power unit and the ability of modularization affect the growth of a renewable energy? It is difficult to answer for the power unit size but the answer to the effect of modularization is yes. The possible, commercially available minimum unit power size,

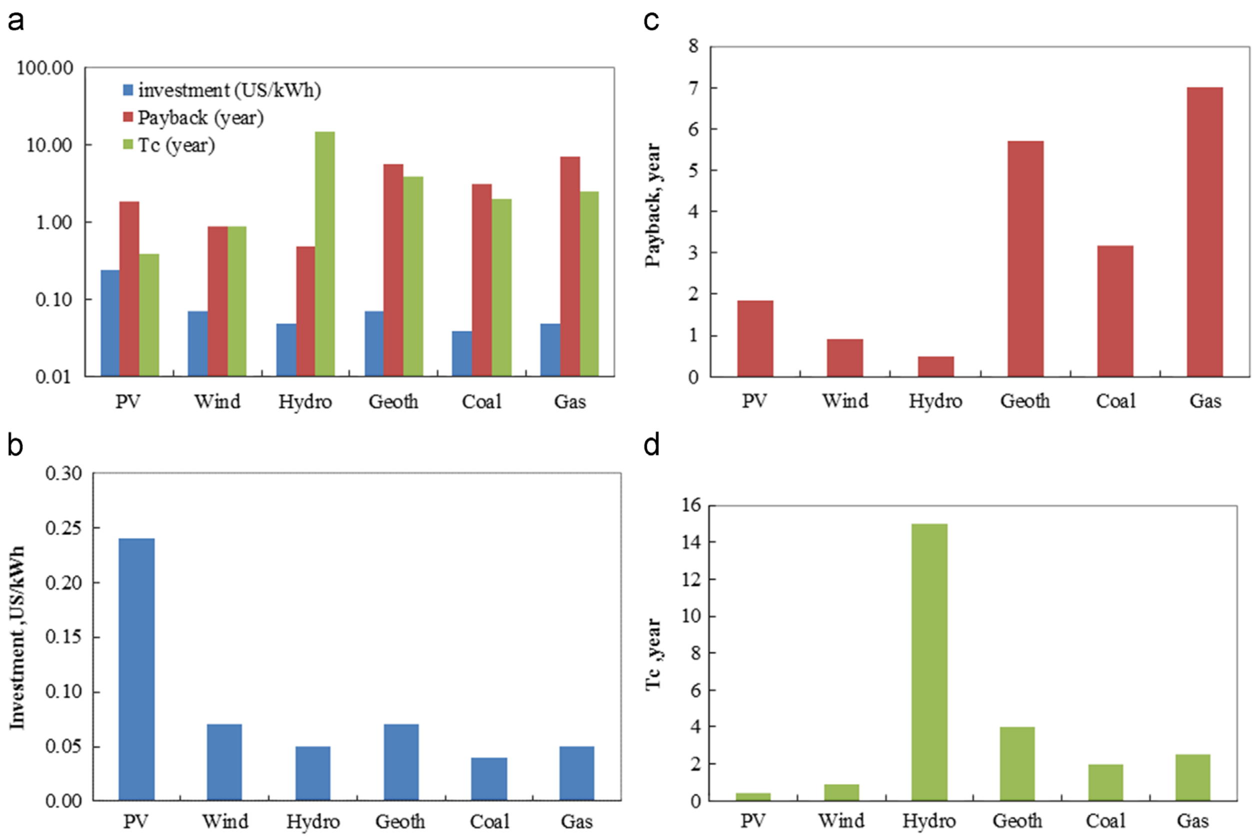

Fig. 7. Comparison of cost, initial investment, payback time, and construction period. (a) All, (b) cost, (c) payback time, (d) construction period.

Table 3
Capacity factor, efficiency, and environmental impacts [24].

	CF (%)	Efficiency (%)	CO_2[a]	Water[b]	Land[c]
PV	8–20	4–22	90	10	28–64
Wind	20–30	24–54	25	1	72
Hydro	20–70	> 90	41	36	750
Geothermal	90+	10–20	170	12–300	18–74
Coal		32–45	1004	78	
Gas		45–53	543	78	

[a] Average greenhouse gas emissions expressed as CO_2 equivalent for individual energy generation technologies: CO_2 equivalent g/kW h.

[b] Water consumption in kg/kW h of electricity generation.

[c] Units: km^2/TW h.

the ability of modularization, and the scalability of the individual renewable energy are listed in Table 5. Also demonstrated in Table 5 is the difficulty to assess the resources of renewable energies. It is known that PV power is highly modularized, followed by wind power. PV also has the smallest commercially available minimum power units. Note that PV power had an annual growth rate of 39% in 2013 only [17]. On the other hand, geothermal has the largest commercially available minimum power units. Geothermal power had a less than 4% growth rate in 2013, only 3.2% in a five-year period from end-2008 to 2013 [17]. It is difficult for geothermal power to be modularized. The fact is that almost each geothermal power plant is different.

Having reliable resources definitions and assessment are equally important for the geothermal energy sector as it is for the oil and gas industry [46]. However, it is extremely difficult to assess the resource of geothermal energy accurately and reliably if comparing with solar and wind energies. The main reason is that geothermal energy depends on the temperature of geothermal formations and is stored underground as deep as thousands of meters. The problem is the difficulty to measure and determine the temperature distribution accurately in underground space. Solar PV's resource is mainly determined by the surface radiation and wind power resource mainly depends on the wind speed. It is much easier to measure both the surface radiation and the wind speed on the ground than to measure the temperature underground.

According to the above data and analysis, the advantages and disadvantages of individual renewable energy are summarized in Table 6.

As observed in Table 6, geothermal energy has many serious disadvantages in terms of current commercially available technologies although it has a lot of advantages.

The main disadvantage of PV and wind may be the capacity factor affected by weather, which causes serious stability problem and high risk to the electricity grid. As reported by Beckwith [52]: sometimes the wind will go from several thousand megawatts to zero in less than a minute. And gas plants cannot come on within a minute. Solar power plants may have similar problems. Geothermal power, on the other hand, is very stable and can provide base load power 24 h/day. Reinjection helps restore the balance and significantly prolongs the lifetime of geothermal power plants. Reinjection of water increases the frequency, but not severity of seismic activity [53].

Evans et al. [24] ranked the renewable energies in terms of sustainability (see Table 7) using data collected from extensive range of literature. The ranking revealed that wind power is the most sustainable, followed by hydropower, PV and then geothermal.

Jacobson [33] also ranked the renewable energies in terms of cleanness (see Table 8). Wind was also ranked No. 1 and geothermal was ranked No. 3 in all of the 7 different types of renewable energies.

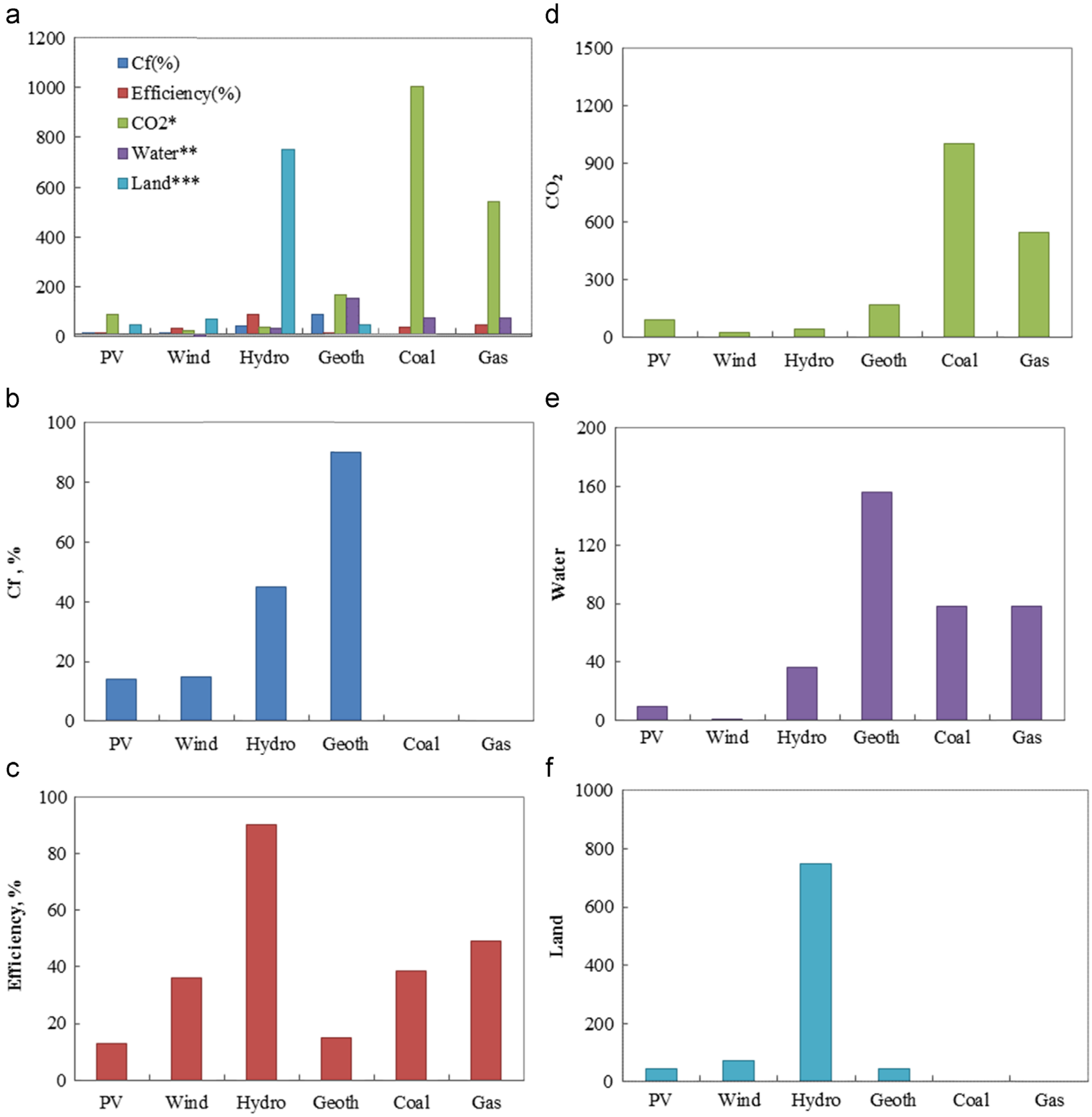

Fig. 8. Capacity factor, efficiency, and environmental impacts. (a) All, (b) capacity factor, (c) efficiency, (d) CO_2: g/kW h, (e) Water: kg/kW h of electricity generation, (f) Land: in the units of km^2/TW h.

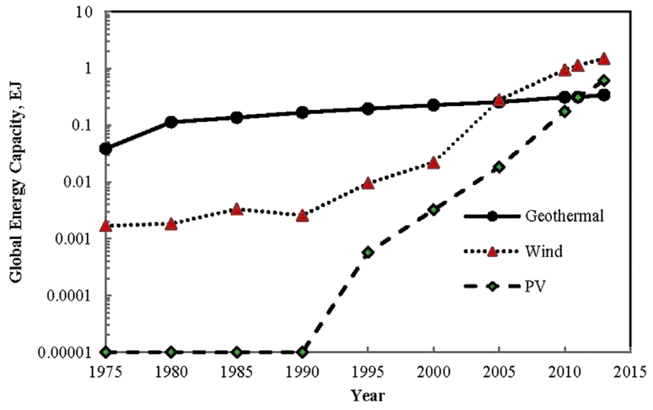

Fig. 9. Comparison of generated energy for individual energy type.

Jacobson [33] pointed out: the use of wind, CSP, geothermal, tidal, PV, wave, and hydro to provide electricity will result in the greatest reductions in global warming and air pollution and provide the least damage among the energy options considered.

6. Solutions to speed up geothermal power growth

It is obvious that geothermal power has been lagged behind wind and solar in terms of both growth rate and installed capacity. As stated previously, geothermal power growth has only a few percent per year. The increase is more or less linear while wind and solar PV power exhibit fast-tracking growth with a clearly exponential tendency.

How do we speed up the growth of geothermal power? Many researchers have tried to answer this question. However, there are

Fig. 10. Solar footprints.
Source: cncmrn.com/channels/energy/20100929/365527.html.

Fig. 11. Wind footprints.
Source: afdata.cn/html/hygz/nyky /20090730/8420.html; ewindpower.cn/news/show-htm-itemid-2482.html.

Fig. 12. Geothermal.
Source: hb114.cc/news/hydt/20090807103400.htm.

Table 4
Qualitative social impact assessment.

Energy	Impact	Gov. Barriers
PV	Toxins: minor–major Visual: minor	Infrastructure (grid) need to be improved
Wind	Bird strike: minor Noise: minor Visual: minor	Infrastructure (grid) need to be improved
Hydro	Displacement: minor–major Agricultural: minor–major River damage: minor–major	No barriers and grid problem
Geothermal	Seismic: minor–major Odor: minor Pollution: minor–major Noise: minor	Infrastructure (grid) depends on location

no easy answers and solutions. Considering the present status and the literature review, some of the solutions and directions are suggested:

- New technology.
- Co-produced geothermal power from oil and gas fields.
- EGS.

Discussion on the above possible ways and approaches to speed up geothermal power growth is addressed as follows.

Table 5
Unit size and the ability of modularization of renewable energies.

	Unit size	Modularization	Scalability	Assessment
PV	1 W	High	High	Easy
Wind	1 kW	High	High	Easy
Hydro	1 kW	Middle	High	Easy–difficult
Geothermal	> 70 kW	Low	High	difficult

6.1. New technology

There have been many great technologies in the area of geothermal power generation. New technologies, however, are definitely required to speed up the growth of geothermal power. Why? It is because it has been tested and shown that current commercially available geothermal technologies can only yield a linear, instead of an exponential, and a very slow growth rate in the last four decades or so.

One of the new technologies that may make breakthrough is the technology to directly transfer heat to electricity, without going through mechanical function. Such a technology exists and has been utilized for a while in making use of waste heat. The core part of this technology is the thermoelectric generator or TEG [54]. TEG has almost all of the advantages of PVs. Plus, the lower limit temperature for generating electricity using TEG may be 30°C. With this advantage, much more geothermal resources might be used and much more power might be generated using TEG technology. Liu et al. [55] has conducted some preliminary study on TEG.

Table 6
Advantages and disadvantages of individual energies.

Tech.	Advantages	Disadvantages
PV	Easy to assess resource Easy to modularize Easy to install Low social impact Easy to scale up Short construction period	Low efficiency High cost Low capacity factor Not weather proof High land use
Wind	Low cost Easy to assess resource Easy to modularize Easy to install Low-medium social impact Easy to scale up Short construction period	Low capacity factor Not weather proof High land use
Hydro	High efficiency Low cost High capacity factor	High initial investment Long construction time Long payback time
Geothermal	Medium-high efficiency High capacity factor Low to medium cost Weather proof	High initial investment Long payback time Long construction time Tough to assess resource Tough to modularize

Table 7
Sustainability rankings [24].

	PV	Wind	Hydro	Geothermal
Price	4	3	1	2
CO_2-equivalent	3	1	2	4
Availability	4	2	1	3
Efficiency	4	2	1	3
Land use	1	3	4	2
Water consumption	2	1	3	4
Social impacts	2	1	4	3
Total	20	13	16	21

Table 8
Rankings of renewable energies [24,33].

Ranking	By cleanness	By sustainability
1	Wind	Wind
2	CSP	Hydro
3	Geothermal	PV
4	Tidal	Geothermal
5	PV	
6	Wave	
7	Hydro	

6.2. *Co-produced geothermal power from oil and gas fields*

There is a huge amount of geothermal resource associated with oil and gas reservoirs for power generation and other purpose [56–60]. There are 164,076 oil and gas wells (2005 data) in China. 76,881 wells have been abandoned, about 32% of the total. These abandoned wells may be served as geothermal wells. The potential geothermal resource in the reservoirs holding these oil and gas wells is huge.

Erdlac et al. [57] reported that Texas has thousands of oil and gas wells that are sufficiently deep to reach temperatures of over 121 °C and sometimes 204 °C. In total there are 823,000 oil and gas wells in the United States. The possible electricity generation from the hot water, estimated by Erdlac, was about 47–75 billion MW h (equivalent to about 29–46 billion bbls of oil).

The main advantage of the co-produced geothermal power is the lower cost than that of EGS because the infrastructure, including wells, pipes, roads, and even grid, are already there.

6.3. *EGS*

One of the hot spots in geothermal industry in recent years was EGS since the publication of MIT report [61]. Many papers have been published in the area of EGS. It is known that EGS has a huge amount of resource. The EGS geothermal resource at a depth from 3.0 to 10.0 km in USA is equivalent to 2800 times of USA's 2005 annual total energy consumption if only 2% of the EGS resource can be recovered [61]. In China, 2% of the EGS resource at a depth of 3.0–10.0 km is about 5300 times of China's 2010 annual total energy consumption [31]. According to the above data, EGS has a great theoretical potential to speed up geothermal power growth. Unfortunately, it is obvious that EGS is presently still at the "proof of concept" stage, as pointed out by Rybach [62].

7. Conclusions

According to the above review and analysis, the following preliminary remarks may be drawn:

(1) Geothermal power has been left behind wind and solar in terms of both growth rate and installed capacity. The main reasons may be high initial investment, long payback time and construction time, difficulty to assess resource and difficulty to modularize. Social acceptance may be another important reason for the slow growth rate of geothermal power generation, which may be more difficult to be overcome than other barriers in some cases or some regions.
(2) Some of the barriers to cause the sluggish growth of geothermal power generation are not independent. The settlement of one barrier may bring about the solutions to other barriers. The main reasons for the slow growth of geothermal power generation may be different in different regions and different countries.
(3) Possible solutions and directions to speed up geothermal growth may be: development and utilization of new technologies such as TEG, co-produced geothermal power from oil/gas fields, and EGS. Currently EGS is still at the stage of "proof of concept".
(4) Although geothermal energy has many barriers, it has many advantages that other renewable energies do not have. These include high thermal efficiency, great stability, weather-proof and base-load abilities, less land requirement and less ecological effect, etc.
(5) Because of its unique characteristics, electricity generation from geothermal energy may have the potential to grow exponentially after the breakthrough of some new power generation technologies suitable for geothermal resource is taken place in the future.

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