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# The Trend of Renewable Energy Growth Until 2050

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## ABSTRACT

It is clear that the rate of energy use is proportional to the world's population, which is growing rapidly. Our most serious problem is the rapid population growth and more energy consumption. The Earth has a population of more than 7 billion, and the population growth rate over the past few decades has been 1.4. Nearly all forecasts show that the world's population is about 11 billion by 2050. So with population growth of 1.4 percent per year, which leads to higher energy demand in the world, the issue of energy consumption growth should be seriously considered. If by 2050, the world's population is 11 billion and energy is consumed as it is today, the world's energy consumption rate will reach 122 TWh, which is 16 times the current energy consumption rate.

It is clear that it is very difficult to provide this amount of energy for 11 billion people, and therefore it is very important to limit the growth of the world's population.

**Keywords:** renewable energy , Biomass energy , Hydroelectricity , Wind energy , Solar energy

## 1. INTRODUCTION

On the April 21, 2017, the United Kingdom, an early leader in the Industrial Revolution, had its first coal free day for several centuries, according to the UK's National Grid [1]. In 1800, as the Industrial Revolution got underway in Western Europe, global primary energy use was around 20.35EJ (EJ¼exajoule¼1018 joule). Global fossil-fuel production, almost entirely coal, was only about 0.3EJ or 106 t [ 2,3 ]. The rest was renewable energy, nearly all biomass energy. In year 2014, according to International Energy Agency (IEA) statistics [4], total primary energy had risen to 574 EJ, with only 67 EJ from renewable energy (RE) sources, mostly biomass used as heating and cooking fuel in low-income countries.

Fig.1 shows the growth of electricity produced from each of the five main RE sources considered in this chapter: biomass energy, hydroelectricity, wind, solar, and geothermal energy, together with global electricity production. What is surprising is that even after 1990, the year of the first Intergovernmental Panel on Climate Change (IPCC) report, the electricity share of RE continued to fall slowly until the mid-2000s [5].

The future of fossil fuels, still the dominant global energy source, is under threat for a variety of reasons. First is its impact on global climate change: most anthropic greenhouse gases (GHGs) annually released derive from fossil-fuel combustion [6].

The second concern relates to the future availability of fossil fuels at affordable prices. Already, much of the global annual production of oil and gas comes from nonconventional sources: deep water and polar oil, oil sands, heavy oils, and gas and oil from fracking. Most of these sources have higher costs—in terms of GHGs, environmental, and monetary—than their conventional equivalents for each joule of final energy.

The third reason is the pollution produced by both their production and especially from their combustion. Although technical solutions such as sulfur dioxide scrubbers and particulate traps are available for fossil-fuel power stations, and unleaded, lowsulfur fuels, and three-way catalytic converters for road vehicles, air pollution from oxides of nitrogen and from very fine particulate matter are still major health hazards, even in OECD cities. In many countries of the industrializing world, a combination of less stringent pollution standards, poor enforcement, rapid urbanization, and rapid growth in vehicle numbers makes air pollution, especially in cities, a major cause of sickness and mortality [7].

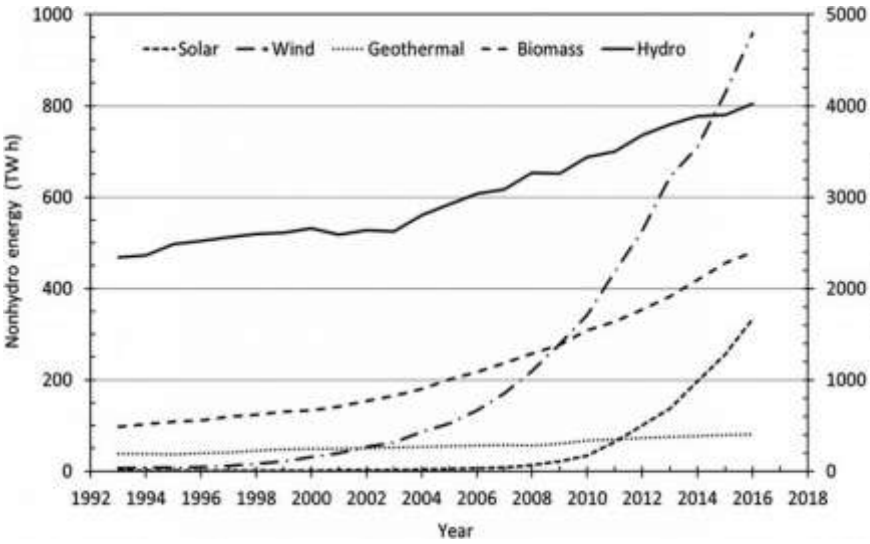

**Fig. 1.** Global RE electricity output vs year 1993–2016 [5].

All energy sources—fossil, nuclear, or RE—must meet a basic criterion: the energy output must be larger (even several times larger) than the energy inputs, when both input and output energy are measured in a comparable way, usually as primary energy. Only for food energy, and novel energy sources still in the experimental stage, can inputs be larger than outputs. We live on a planet with finite resources, and for economic reasons, high-quality energy resources are usually developed first. Hence, as annual output of RE sources rise, or cumulative output of fossil fuels or uranium rises, progressively lower-quality sources must be tapped. For fossil fuels, this trend is already evident: a rising share of oil is from the deep ocean, the Arctic, and bitumen sands, and natural gas from fracking. The consequence is an early rise in the energy return on energy invested (EROEI) as the technology is developed and improved, then a peak value, followed by a steady fall in EROEI for each fossil fuel. Oil and natural have already passed their peak value, as have fossil fuels overall, but the EROEI for coal is still rising, as documented by Court and Fizaine [8].

Most RE sources can be expected to follow the same trend as for fossil fuels, with the possible exception of solar energy. This eventual fall in EREOI will occur for several reasons. First, the declining quality of the resource base (e.g., lower wind speeds, less suitable hydro sites, lower temperature geothermal fields) will tend to lower the energy output for a given energy conversion device compared with higher quality resources. Second, as we will argue, the technical potential for most RE sources is limited, even compared with present global primary energy use, with the exception of wind, solar, and wave energy. But the latter group are all intermittent sources of energy, necessitating energy storage and the inevitable energy losses this entails, if they are to replace fossil fuels. Further, since we need other forms of energy apart from electricity, conversion to other energy carriers (perhaps hydrogen or methanol) will also be needed. Third, even if the world soon acts decisively to mitigate climate change,
further climate change will occur; which could adversely affect the EROEI of planned and even existing RE production. Most of the global estimates for the various RE sources have not considered EROEI values, and so will likely be overestimates of potential [9,10].

What is the future of global energy consumption? The oil company BP has projected global commercial energy use (i.e., excluding fuel wood) by fuel and region out to the year 2035 [11]. Overall primary energy use was expected to rise from 550EJ in 2015 to 720 EJ in 2035, with nearly all the increase coming from non-OECD countries. All RE sources, including hydro, were forecast to roughly double from their 2015 level of 52.7EJ to 119.6 EJ, in 2035, or one-sixth of the total. One difficulty with interpreting these numbers is that BP and the International Energy Agency (IEA) use conflicting methods for calculating the primary energy values of nonheat energy sources like wind and PV electricity. The IEA use a one-to-one conversion, while BP factor values by the inverse of modern thermal power plant efficiency [12]. The differences will become more pronounced if these nonthermal energy sources come to dominate total energy production. Use of each fossil fuel—coal, oil, and natural gas—was also projected to increase, with most of the growth coming from natural gas. Evidently, BP did not foresee any drop in CO2 energy emissions by 2035. Bioliquids for transport would also remain marginal, rising from 3.1 to only 5.4EJ over the period. Similarly, the US Energy Information Administration (EIA) projected global energy-related CO2 emissions to continue to grow at 1.0% per year over the period 2010–40 [13]. Annual fossil-fuel use was likewise projected to continue to rise.

## 2. BIOMASS ENERGY

Biomass is defined as all non-fossil material of biological origin. Every biomass-based energy process begins with sunlight and the production of a chemical element. This complex step, called photosynthesis, leads to the production of glucose. Subsequent biochemical transformations lead to the production of a large number of elements, some of which have a very high economic value.

However, for engineers who care about biomass extraction, important products are glucose and its polymers (starch and cellulose), some sugars (hemicellulose) and lignin. At best, photosynthesis proceeds with less than 8% efficiency. When the final product is ready for consumption, significant amounts of energy are consumed in fertility, harvesting, transfer of raw biomass, extra water extraction and extraction of the desired fuel.

Overall efficiency is usually less than 1%. This is a prime example of an applied energy process that, while infinitely unprofitable, is commercially important primarily because of its economic and biological benefits.

Fig.2 shows the growing trend in the use of biofuels in the world. This estimate shows the amount of energy production from biomaterials by 2020, which reaches up to about 600TWH, and this is a significant amount. The chart also shows a significant difference between the use of this energy in Europe and other parts of the world, given the small size of the continent. In contrast, little attention has been paid to the capacity of this type of energy in the Middle East [14] .

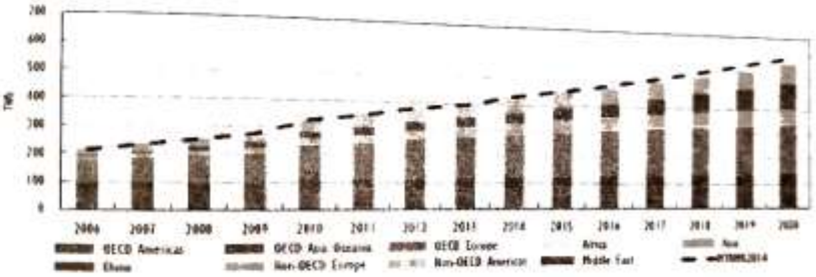

**Fig.2** Energy production from biomaterials and production forecasts by 2020 in different parts of the world[14]

### 2.1 Bioenergy in 2050

Bioenergy is the oldest form of nonfood energy, with its origins perhaps 500,000years ago. Chances for further major technical breakthroughs in combustion appear small, with most research now concentrated on topics such as increasing crop productivity and converting cellulosic materials to liquid fuels for transport. At present, all such liquid fuels are derived from edible feedstocks—grains, sugar, and edible oils—which raises ethical questions in a world with an estimated 800 million people facing absolute food shortages [15]. The present effort put into cellulosic conversion may be misplaced: from an energy or GHG reduction viewpoint; it is better to use biomass directly to produce electricity, particularly if it displaces coal or oil as power plant fuels, rather than convert it to liquid fuels for transport [16].

Global land-based Net Primary Production (NPP) is the total mass of living plant matter produced annually, minus plant respiration. Terrestrial NPP, estimated at 2000 EJ [17], obviously fixes a theoretical upper limit on the human appropriation of NPP (HANPP). Estimates for global HANPP vary, depending upon which items are included or excluded, with values ranging from 10% to 50% [18]. Since nonhuman nature provides ecosystem services (apart from obvious ones like food and timber) on which we are dependent, any major rise in HANPP could merely be trading growth in one set of ecosystem services (e.g., food) with a corresponding loss in others (e.g., biodiversity, pest control). Axel Kleidon [19] estimated present HANPP as 40%, and based on a model of the vegetation-climate system, argued that for HANPP values beyond about 45%, any percentage rise would produce feedbacks that would reduce global NPP, and eventually, the absolute level of HANPP measured in energy or mass units.

The world population in 2015 stood at 7.35 billion; the UN [20] expect this to rise to 9.73 billion by 2050. If present trends for per capita income growth also continue, there will evidently be increased demand for all uses of biomass, raising the question of which ones should get priority. Clearly, from an ethical viewpoint, food should come first: we should produce enough food for the likely expanding human family. Nevertheless, this does not necessarily imply that present dietary trends are followed. If instead of expanding animal products as at present [18], the world moved toward a more vegetarian diet, agricultural production could be reduced, given that animal products need far more inputs (and produce more GHGs) per kilojoule of food energy than nonanimal products. Nevertheless, the FAO [19] anticipate that output of both grain and animal products will continue to rise, as will agricultural land area. Increasing agricultural yields can reduce the inputs of land needed for food production, but the FAO saw yields only growing slowly. Future productivity gains will be more difficult to make, particularly in the face of on-going climate, uncertainty about future phosphorus availability, biodiversity loss, and other changes. And although land productivity (output per hectare) has risen, the same is not true for energy productivity. Historically, food was produced with a much lower ratio of energy inputs to energy output—this ratio declined by more than an order of magnitude in the 20th century [20].

In 2014, although the nonfuel production of timber was 1836Mt (1836_106 t), up from 1700Mt in 1990 [19], timber is losing share as a construction material, as are natural fibers like cotton [18]. Yet in terms of meeting a given building function, such as the framing for a four-storey apartment block, timber has a much smaller carbon footprint than steel or reinforced concrete. This suggests that for climate mitigation, biomaterials should be expanding, rather than contracting as at present, their share of the market. Such a biomaterials expansion would lower the global potential for bioenergy, assuming that all biomass uses together face a global upper limit—that for HANPP.

Clearly, there is no simple answer to the question: What is the global technical potential for bioenergy? It all depends on future consumption of biomass for biomaterials and food. The input resources necessary to meet food needs in 2050 involve both ethical and technical questions. The huge range of estimates in the literature for 2050 bioenergy technical potential reflect this uncertainty: values vary from a low of 10–60EJ to an upper value of over 1500EJ [10]. Since this upper value is 75% of the entire global terrestrial NPP, it is clearly unrealistic. Given the superior GHG savings possible with using biomaterials as a substitute for more energy- and GHG-intensive materials, as well as rising food needs, values toward the lower end of the range are more likely.

However, the three human uses for biomass are not fully independent of each other. Human wastes can be used to produce methane from both sewage treatment works and from landfill gas. Some agricultural and forestry wastes can be used for bioenergy, although most will need to be retained in situ to maintain soil fertility and reduce wind or water erosion. Finally, biomaterials, particularly construction timber, after the end of its useful construction life—which may involve its reuse in some other construction project—can be combusted for energy.

## 3. HYDROELECTRICITY

In the early years of electricity, most was produced from hydro, but was soon overtaken by fossil fuels burnt in power stations. Today, despite rapid growth in recent decades of first wind, then solar electricity, hydro still dominates RE electricity production [5]. The hydro potential in OECD countries is now largely exploited; most of the remaining potential is in Asia, Africa, and South America [21]. Hydropower is a mature technology, and little in the way of technical advances can be expected. It also has EROEI values greater than other RE sources [22]. There are even indications that the energy ratio for new hydroconstruction is falling globally, in that the annual electricity output per megawatt of installed power over the period 1994–2011 was <40% of its value in the year 1993 [21].

### 3.1 Hydroelectricity in 2050

Hydroelectricity cannot be readily stored. But unless the hydroplant is a simple run-ofthe- river installation, electricity can be generated on demand because of the gravitational energy of the water stored behind the dam wall. It is likely that by 2050, most of the world’s remaining technical potential for hydropower will be utilized. But some potential will remain unexploited—and so annual electric output will still be well below 30 EJ for several reasons. First, ongoing climate change will add to uncertainty about future catchment precipitation levels and the season distribution of annual river flows, although some areas (such as Arcticdraining rivers in northern Europe) will see conditions favorable for further hydro output. In some mountainous areas, such as the Himalayas, hydropotential could show a temporary increase, fuelled by continuing loss of glacier mass [6,23]. This uncertainty will impact on the economics of hydrodevelopment, given that dam structures can have an expected lifetime of 100 years or so.

Second, extreme rainfall events are expected to increase in frequency. The soil erosion potential varies nonlinearly with rainfall intensity (and so will catchment area landslides into the reservoir), so that sedimentation rates of hydroreservoirs will increase, shortening their service lives. In the Amazon basin, another factor could seriously affect the basin’s vast hydropotential. Deforestation, which is still occurring in the Amazon, initially increases river flows, and thus hydropotential, because of less transpiration from trees.

But beyond a certain level of basin forest loss, further deforestation reduces hydropotential. The modeled results of Stickler et al. [24] showed that hydropotential could be reduced to only a quarter of its full potential if 40% of forest cover is lost. This reduction occurs because in the Amazon the “rainfall systems are maintained, in part, by the forest itself through contribution of water vapor to the atmosphere through ET and through its associated influences on land–atmosphere energy exchange” [24]. Presumably any comparable loss of tree cover from climate change would have a similar effect.

## 4. WIND ENERGY

The use of wind energy dates back to ancient times, when wind was used to propel sailboats. It seems that the wider use of wind turbines in Iran has been for grinding wheat.

In Europe, wind turbines were first used in the 11th century. Two centuries later, the turbine became an important tool, especially in the Netherlands. Also, with the help of air pumps and sawing machines, progress was made in the United States.

Of course, determining energy costs at best is also unreliable. Depending on the assumptions made and the computational model used, the costs change significantly. The calculated cost depends on several factors, including:

1) Investment cost
2) The cost of fuel, of course, is zero for wind and hydroelectric power plants.
3) Labor and maintenance costs
4) The cost of not being used
5) The cost of land

Although the actual cost of wind energy may be unknown, it is safe to say that the cost has dropped dramatically over the past 15 years. The sale of wind-generated electricity under the so-called Green Pricing method became popular. In this way, consumers were committed to buying electricity for at least a year in the form of 100-kilowatt one-month packages typically priced at 2.5 cents more than the usual rate per kilowatt.

Therefore, consumers with environmental thinking can volunteer to support energy sources without pollution [25].

## 4.1 WIND ENERGY IN 2050

If the linear increases in output from 2008 to 2015 continue in coming decades, wind could be expected to supply 3985TWh (14.3 EJ) globally in 2050, compared with the 2015 output of 841TWh (3.0 EJ). Although this growth represents a more than fourfold increase, wind will still only be a marginal source in 2050, with estimates of total primary energy use then as high as 1000EJ [12]. Even with strict land constraints on turbine placement, this value of 14.3EJ is still well below the global technical potential of wind energy [2]. Slow growth, rather than resource limits, is what could prevent wind energy becoming a major energy source by 2050. In any case, wind turbines are now also being sited offshore, which increases the global wind resource base. Although more expensive to install and maintain, this cost is offset by higher wind speeds—and less public opposition.

Since the rebirth of wind turbines in the 1980s, blade diameters and rotor heights have steadily risen; the greater rotor heights (up to 200m) enable both higher wind speeds and less wind speed variation across the blades. Even higher wind speeds could be obtained if the turbines could be placed at much greater heights, and hence greater electricity output per turbine of a given rating. Various proposals include turbines borne aloft by tethered balloons and tethered self-propelled turbines. Another proposed concept would be based on airborne kites [26]. As with ground-based turbines with an average rated output of, for example, 5MW, many thousands would need to be deployed for significant electricity production. Great care would need to be taken to lessen the dangers to aircraft, birds, and even people on the ground from either falling cable or the turbines themselves. If wind energy continues to rise at only a linear rate, land and shallow sea locations will be ample, and air-based turbines are unlikely to be more than novelties, even in 2050.

## 5. SOLAR ENERGY

The history of the use of solar energy dates back to many years before Christ. In the year 700 BC, solar energy was used to heat buildings in Greece. In Iran and other countries, there is evidence that humans in the design of residential houses, palaces and large and important mansions have paid attention to the issue of lighting and heating using solar energy.The sun can be considered as a pure and endless source of energy, the use of which has long been of interest to mankind. Today, the use of solar energy, in addition to reducing pollution from the use of fossil fuels, has found many attractions from the perspective of new technologies. These include heat pipes, thermoelectric, fuel cells and nano. Also, very interesting innovative applications have been proposed for the use of solar cells, and small and large solar devices and devices have been commercialized and can be seen in stores and shopping and tourism centers.

Due to the good sunlight in many cities of Iran, solar energy can be considered as one of the important sources of energy supply in the country in the coming years. It is predicted that with the reduction of the price of solar cells and the progress of technical knowledge in the country and with proper management in the coming years, significant progress can be observed in this field. Iran is located in the solar belt region, and studies show that the use of solar equipment in Iran is appropriate and can provide part of the country's energy needs.

Iran is a country that, according to experts, with 300 sunny days in more than two-thirds of it and an average of 4.5 to 5.5 Kw/h of square meters per day, is one of the countries with high solar energy intake. According to some solar energy experts, if Iran equips its desert area with radiant energy receiving systems, it can also provide the energy needed by large parts of the Middle East region and be active in the field of electricity export [27].

### 5.1 Solar energy in 2050

Recent growth in global solar electric production has been exponential, and given the possibility of technical breakthroughs, any predictions of future output are unlikely to be useful. It should be remembered that wind energy also experienced an exponential growth phase, before slowing to linear growth over the past decade. Because of its intermittency, some researchers have put forward ambitious schemes to avoid this problem. One, first proposed in the mid-1970s, is solar satellite power (SSP). The proposal would involve a fleet of satellites, placed so as to receive 24-h insolation. Each would carry an array of PV cells on a lightweight frame. The electricity generated would be converted to microwave energy, beamed to Earth receiving stations, and then converted back to electricity. The costs of satellite placement would be high, and since energy conversion losses would occur at each stage from insolation through to electric power generation on Earth, EROEI values could be low.

Other proposals would see vast solar farms installed in each of the world's deserts, so that both seasonal and diurnal variations in insolation could be circumvented. Evidently this scheme would require a worldwide interconnected grid, the building of which would be the greater part of this hugely expensive Scheme [28]. A recent variant—the Desertrec scheme—would build large solar and wind farms in the deserts of north Africa and the Middle East to supply European as well as local energy needs [29]. It is doubtful, however, whether Europe would wish to become largely dependent for its electricity supply on distant countries. At present, very little electricity is exported across borders [4]. Furthermore, the project would still not solve the intermittency problem.

Solar electricity, particularly from PV cells, is different from other RE sources in several ways. Not only is its resource base orders of magnitude higher, but the monetary costs of PV cells of a given rated capacity have decreased exponentially with time, because of continuous improvement in the materials used. Further breakthroughs are promised [30]. But there are several factors that need consideration.

The first is that the expected life of PV units may be much lower than anticipated—closer to 17years rather than 30years [31]. Second, the development of higher efficiency PV cells may rely on exotic materials, which have a low global resource base, and will prove increasingly costly to extract in monetary, energy, and environment terms. We may thus be substituting one environmental problem for another [32,33]. Third, PV cells are only part of the total system costs, and the other costs, particularly for supporting structures in solar farms, are less likely to see further cost reductions per installed watt.

## 6. GEOTHERMAL ENERGY

The temperature gradient in the Earth's crust is 17 to 30 degrees Celsius at a depth of one kilometer. For example, the mines are very hot and often require cooling of the workers' work environment in the mines. Exits of igneous rock masses with very high temperatures (about 1000 degrees Celsius and above) from the crater of volcanoes indicate the existence of high temperatures in the depths of the earth. Figure 3. shows the tectonic plates of the Earth with the volcano. In fact, from the pages, it examines and studies the large-scale movements of the Earth's lithosphere (the Earth's crust and the Earth's upper part). The lithosphere consists of several massive plates (tectonic plates). In some cases, these huge plates are made up of a small number of plates that form continents and seabed. These plates are constantly moving, and as a result of their collisions, phenomena such as earthquakes, volcanoes, mountain formation and other phenomena are obtained. The movement of these plates is estimated from the lowest limit of zero mm per year to the highest limit of 100 mm per year, depending on their type and condition.

**Fig.3** Earth's tectonic plates with volcanoes[34]

Geothermal exploration programs are based on the use of ground-level evidence along with geospatial and geophysical mapping data to identify areas with geothermal potential. Figure 4.

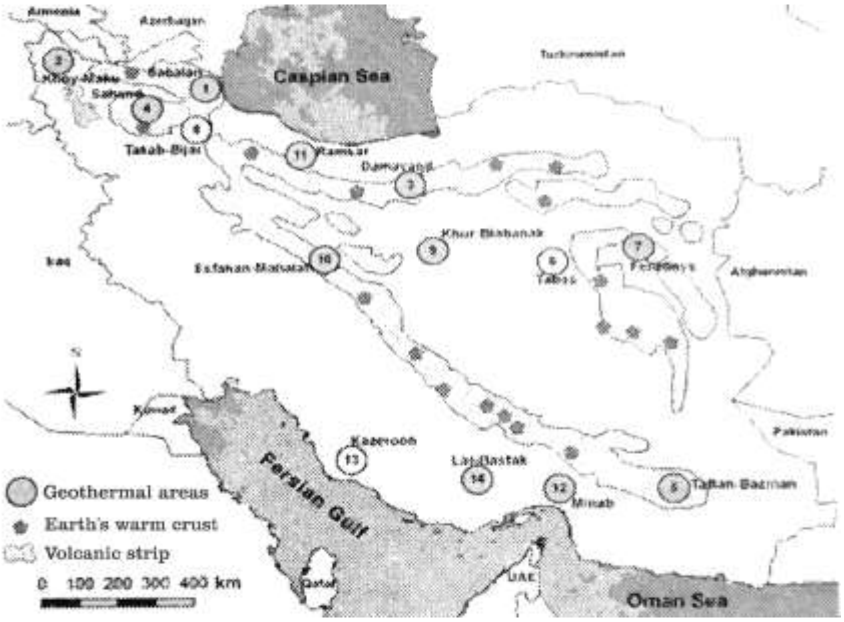

**Fig4.** Map of geothermal resources in Iran, identification and numbering of 14 geothermal areas based on the importance of those areas [35].

Shows a map of geothermal resources in Iran. 14 geothermal areas are numbered according to their importance. According to Figure 5. The plateau of Iran can be divided into 5 areas of general tectonic structure, which includes the Zagros belt, Sanandaj belt, Sirjan, Central Iran, Alborz mountains and Koye hot zone [14].

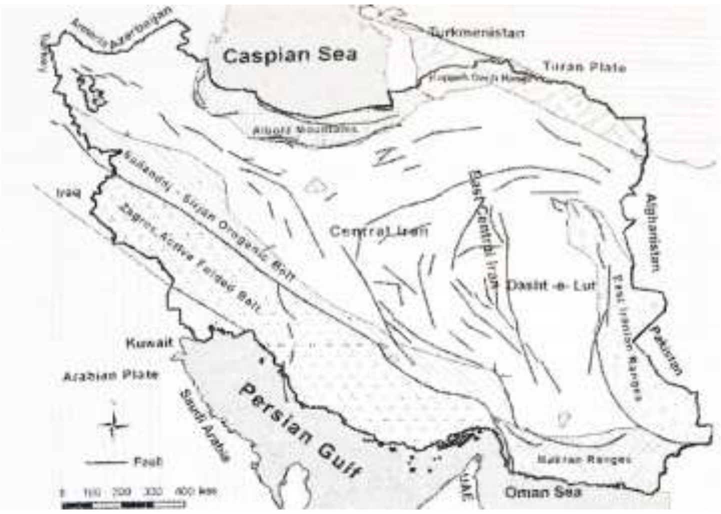

**Fig.5** The general structure of the tectonic regions of Iran [35]

### 6.1 Geothermal energy in 2050

Global growth in geothermal electricity output has been linear for the last 3–4 decades, and if this trend were to continue, geothermal installed capacity will ris from 13GW in 2015 to roughly 20GW by 2050. At the present average capacity factor output would only be about 115TWh, a minor fraction of even the 2015 global electricity output of 24,100TWh [5]. Such high rates of utilization evidently are not sustainable in the long run. Even for electricity production from high temperature sources, it is found economic to "mine" the heat source, resulting in depletion of the geothermal field, and the need for perhaps decades of recovery time before it can be used again.

The energy conversion devices for geothermal electric production, are like wind turbines, a mature technology. Just as some wind energy researchers are looking to go higher, to capture the stronger and more reliable winds, so geothermal researchers are considering utilizing the higher temperatures that progressively occur with depth below the surface—enhanced geothermal systems (EGS). In 2006 the Massachusetts Institute of Technology published a detailed study on EGS in the United States context, and gave a resource base for the United States in the millions of exajoules [36]. To assess its feasibility, two parameters are important to consider: the temperature and the depth of the geothermal heat source. The study showed that no heat sources above 200°C existed at depths above 4 km. Since the study also demonstrated that well monetary cost rises exponentially with depth, it is probable that input energy costs and final electricity costs would also rise nonlinearly with borehole depth. Disappointingly, no energy analysis of EGS was undertaken in this otherwise detailed report [37].

## 7. OTHER POSSIBLE RENEWABLE ENERGY SOURCES

A number of other possible RE sources are under consideration, many of which can be grouped together as ocean energy sources. This list includes tidal energy, wave energy, ocean current energy, and ocean thermal energy conversion (OTEC).

The global scope for tides as an energy source is very small, since the total tidal energy resource base is only 75EJ, of which about 73EJ is dissipated at coastlines, but in most cases the tidal range is too small for effective utilization. The only large commercial plant for decades was on the Rance estuary in France, completed in 1966 and still supplying 0.5TWh or 0.002EJ of electricity annually. In 2011, a slightly larger plant (0.55TWh) opened in South Korea, and several others are in the planning stage. None have a power output of more than about 250MW [38]. The larger tidal energy projects dam a bay and function in a manner similar to low head hydro plants, but a less environmentally disruptive approach is to place turbines in tidal flows in river estuaries or straits. One such installation in a tidal flow strait near Belfast has a power output of 1.2MW [39].

The main potential ocean energy source is wave energy, which occurs because some of the planet’s wind energy is transferred to the surface waters by shear forces. Vast numbers of devices to capture wave energy have been invented, and several new designs have undergone ocean trials. Lo´pez et al. [40], in their review article, listed the advantages and disadvantages of wave energy.

- Its power density, at 2–3kWm$^{-2}$ , is an order of magnitude greater than solar energy, and almost an order of magnitude greater than wind energy.
- Energy is available around 90% of the time, much greater than for wind or solar energy.
- Wave energy is well matched to demand, given that about 44% of the global population presently live within 150km from a sea coast [39]. A related point is that wave energy is a potential RE source for nearly all countries with a sea coast, since it can be harvested on the open seas or at the coast.

Drawbacks of wave energy mainly result from the very variable height, frequency, and direction changes (for off-shore converters) of the waves, which all complicate design of the conversion devices. In many offshore locations, the converters must be designed to withstand the force of heavy waves, which increases both their cost and the difficulty of maintenance. At present (2018), despite several sea trials with prototype devices, no wave energy is being generated, despite the $US 735_106 investment over the 2004–14 period [39]. As an example of recent designs, the Pelamis Wave Power device is segmented, and power is generated by the relative movement of the segments. It was the first grid-connected wave energy converter, with different versions deployed off both the Scottish and Portuguese coasts, but are now no longer in operation.

The temperature difference between the tropics and the polar regions drives the various ocean currents, such as the Gulf Stream. Some researchers have proposed tapping into the kinetic energy of these currents as they pass through constrictions like the Straits of Florida [41].

Another method of extracting energy from the ocean is through OTEC, which uses the temperature difference between the surface tropical oceans and the colder water 1 km down to run a heat engine to generate electricity. Since the deep cold waters are really part of the return flow of the major ocean currents, the global OTEC potential cannot be considered separately from that for energy extraction from surface (ocean) currents. Because the temperature difference is at best only about 20–25°C, electricity is generated at low efficiency, and very large volumes of water must be brought to the surface for each kWh produced. EROEI values will therefore be low.

Further, while small shore-based OTEC plants avoid this problem (and can also be used to coproduce fresh water), for globally significant production, OTEC plants will need to be ship-based and continuously move to maintain the necessary temperature difference. The electricity produced will have to be converted to some other energy form such as ammonia or hydrogen, and periodically shipped back to shore. The energy costs of water pumping and ship fuel, and of building the plant and the ship, and the energy losses in energy conversion (and reconversion if needed) will mean a very low EROEI value for OTEC electricity [42]. Each year _35,000–40,000km3 of low salt content fresh water enters the world’s oceans [43], which have an average salt content of about 3.5%. The resulting osmotic pressure at the interface is theoretically capable of generating 95EJ of energy. [44]. At present this energy source is untapped, and there appear to be no plans for its development, possibly because of its technical difficulty, and its likely high environmental costs.

## 8. DISCUSSION

In the year 2050, we have argued that RE will be operating under very different conditions than those that prevail in 2018. A high global carbon price is likely to be in place, with the price having progressively risen over time. In 2016, fossil-fuel use was still increasing globally. If further high output continues, it is likely that by 2050, the remaining fossil fuels will be much more costly to extract than at present, and will carry higher GHG and general environmental costs. Despite much research and even limited field trials, it is probable that in 2050 geoengineering will only be deployed locally. Despite its relatively low estimated monetary costs, it carries the risk of adverse environmental effects, particularly on regional precipitation, and hence lacks global political consensus. By 2050, carbon sequestration is likely to have been implemented on a small scale, but will probably be regarded as at best a minor technique for climate mitigation. All these factors will generally favor RE sources over fossil fuels, enabling RE output to steadily expand. On the other hand, over the next decade or so, it is possible that most carbon reductions will come from energy conservation and energy efficiency measures. The resulting spare capacity in fossil-fuel power stations could inhibit growth of RE output.

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