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Emerging renewable and sustainable energy technologies: State of the art

Akhtar Hussain[a,*], Syed Muhammad Arif[b], Muhammad Aslam[c]

[a] Department of Electrical Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon, Republic of Korea
[b] College of Information & Communication Engineering, Sungkyunkwan University, 2066 Seobu-ro, Jangan-gu, Suwon, Republic of Korea
[c] Department of Electrical Engineering, Myongji University, 116 Myongji-ro, Cheoin-gu, Yongin, Republic of Korea

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ABSTRACT

In this paper, five most emerging renewable energy sources are analyzed. These emerging renewables are either special or advanced forms of the mainstream energy sources (solar, wind, geothermal, biofuels, biomass, and hydro) or brand new technologies. The five emerging renewable technologies discussed in this paper include marine energy, concentrated solar photovoltaics (CSP), enhanced geothermal energy (EGE), cellulosic ethanol, and artificial photosynthesis. Marine energy is divided into wave energy, tidal energy, tidal/ocean currents, salinity gradient, and ocean thermal energy conversion. CSP technologies are divided into parabolic troughs, linear Fresnel reflectors, parabolic dishes, and solar towers. The process for developing EGE reservoirs is also explained in detail. Cellulosic ethanol energy extraction is explained for both cellulolysis and gasification. Artificial photosynthesis is explained by considering semiconductor particles, electrolyzers, artificial leaves, and dye-synthesized solar cells. Each emerging renewable source's explanation is followed by its market share, challenges, implications for increased adoption, future prospects, and drawbacks.

1. Introduction

The essence of energy to our society is growing to ensure the quality of life and to smoothly run the other elements of our economy. Energy-resource usage has been considered as the most important and ongoing issues of the modern time. About two billion people across the globe lack electricity today [1]. The reliance on technology, enhanced living standards of developed countries, and continuous increase of population in the developing countries certainly results in the rise of demands for energy. In order to fulfill the energy demands, consumption of fossil fuels is increasing, resulting in depletion of the ozone, climate changes, environmental issues, and increased health risks to the living creatures on earth. In order to maintain the thermodynamic balance of the planet at a constant temperature, the amount of absorbed energy as solar radiations must be equal to the amount of energy emitted back into space at longer wavelengths, infrared [2]. The greenhouse gasses in the atmosphere absorb and reemit infrared radiations while keeping the lower atmosphere and earth's surface warm [3]. It is observed in the survey [4] that fossil fuels and cement are increasing their shares in global CO_2 emission and established forests are decreasing their role as CO_2 sinks.

The increased CO_2 results in a significant increase in the average CO_2 level in the atmosphere, which was 280 ppm in the pre-industrial era and has been increased to 390 ppm [5]. In order to keep the earth safe and to counter the potential environmental threats sustainable and pollutant free technologies have been introduced, known as renewable energy technologies.

Energy sources can be divided into three main categories: fossil fuels, nuclear resources, and renewable energy sources [6]. Renewable energy sources have a potential to play an important role in the world's future. Renewable sources can be used to produce energy again and again i.e. solar energy, wind energy, geothermal energy, marine energy, biomass energy, biofuels, and many more [7]. Renewable energy sources have the ability to provide energy free of air pollutants and greenhouse gasses by emitting zero or nearly zero percent of these gasses [8]. It is a reliable, affordable, and environmentally sustainable way to harvest the renewable energy in a decentralized manner to meet rural and small-scale energy needs [9,10]. Several renewable energy technologies are in practice in the 21st century, but many of these technologies are still under development.

Currently, renewable energy sources supply about 23.7% of the total world energy demand [11], which was 2% in 1998 including seven exajoules of modern biomass, and two exajoules of all other renewable sources [12]. Currently, some of the renewable energy technologies i.e. hydropower, wind energy, solar energy, biomass energy, biofuels and geothermal energy are now mainstream and contributing.

towards the safety of the planet earth and its living creatures. Apart from these mainstream renewable technologies, there are some new

* Corresponding author.
E-mail address: hussainakhtar@inu.c.kr (A. Hussain).

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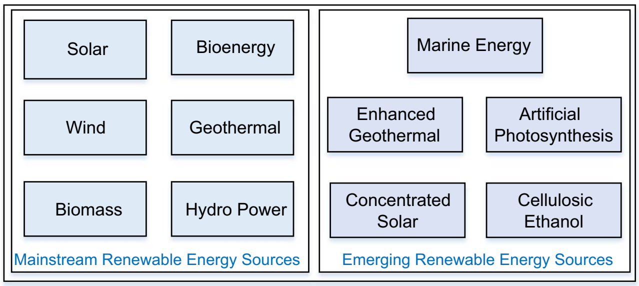

Fig. 1. Mainstream and Emerging Renewable Energy Sources.

renewable energy technologies, which are equipotential and sustainable for countering the greenhouse gasses and air pollution risks to the earth. These emerging renewable technologies comprise of marine energy, concentrated solar photovoltaics (CSP), enhanced geothermal energy (EGE), cellulosic ethanol, and artificial photosynthesis (AP), and many more. An overview of these mainstream and emerging renewable energy sources is shown in Fig. 1.

In this paper, the five emerging renewable technologies mentioned above are discussed. Potential of each emerging technology, different technologies in the energy extraction process, sustainability, current state of development, future prospects, and drawbacks of each technology are analyzed in detail. This paper is aimed to help the researchers get insight into the new and emerging renewable energy technologies and their current state of development.

This paper first explains the development of renewable and sustainable energy (mainstream energy sources especially). Then emerging technologies are discussed, followed by an explanation of each emerging technology in detail. Each section is concluded by future prospects and drawbacks of each technology. Finally, conclusions and a summary of all the five emerging renewable technologies are presented.

2. Renewable and sustainable energy development

In the previous section, an overview of both the mainstream and emerging renewable technologies has been presented. However, in order to be a sustainable energy source, the energy source should fulfill the defined social, economic, and environmental aspects. Fig. 2 provides a comprehensive definition of the sustainable development process.

At present, more mature and reliable renewable energies are on the rise and competitive to the conventional energy sources. Shore wind, solar, concentrated solar, geothermal, marine energy, and bio-energy are on track; and in some circumstances, they have overcome the economic constraints. The share of renewable energy sources in the global final energy consumption is increasing.

In 2012, renewable energy provided an estimated 19% of the global final energy consumption, and it increased to 23.7% in 2014 [11]. The

Aspect	Bearable	Equitable	Viable	Sustainable
Social	○	○		○
Economical		○	○	○
Environmental	○		○	○

Fig. 2. Sustainable Development Scheme (Source: Sustainable Development Portal).

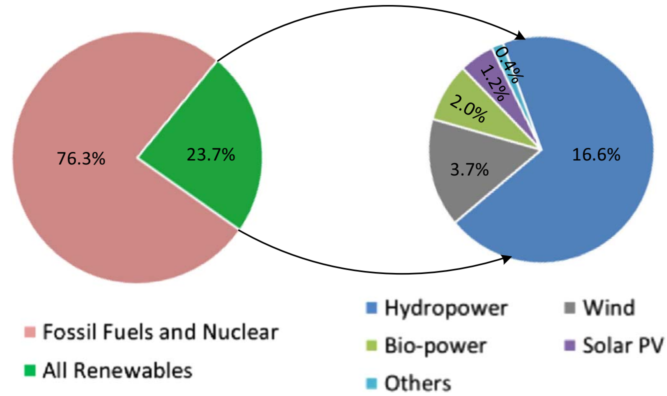

Fig. 3. Estimated Renewable Energy share of Global Energy [11].

contribution of different renewable energy sources to the world's renewable energy can be seen in Fig. 3. The year 2015 has been an extraordinary year for renewable energy, with the largest global capacity additions seen to date [11]. It has been observed that, among various renewable energy sources, the hydropower share is on the top at 16.6% of the total 22.7%, while the wind, biopower, and solar power shares are 3.7%, 2.0% and 1.2%, respectively. Other renewable energy sources, concentrated solar photovoltaic, marine, geothermal, and others contribute to only 0.4% as depicted in Fig. 3.

It has been reported in the global status report (GSR) on renewables in 2016 [11] that the most significant growth in sustainable energy occurred in the power sector with the global capacity exceeding 1560 GW (including small hydropower). The investment on the renewable energy resources has also increased significantly over the last ten years. A summary of the investment over last 12 years is shown in Fig. 4. A total of 40billion USD was invested by global investors in the field of renewable energies in 2004. The investment kept on increasing and reached 279billion USD in 2011; but after 2011, it began decreasing. This decline is due to the drastic reduction in technology costs especially for solar PV, which saw a record of new installations in despite a reduction in dollar investment [13].

A considerable shift in the global perceptions of renewable energy has been observed since 2004. The rapid progress in the technological field of several renewable energy technologies in the last decade has shown that their potential is achievable. Renewable energies have advanced closer to realizing that potential within the last decade [13] and many technologies are at par with conventional energy generation technologies.

According to GSR-2016, in terms of the total installed renewable power capacity, China, the United States, Brazil, Canada and Germany remain the top countries. China, the United States, and Germany were the also the top countries for non-hydrogen capacity and are followed by Spain, Italy, and India. From an investment point of view, Mauritania, Honduras, Uruguay, Morocco, and Jamaica were among the top countries for investment in new renewable power and fuels

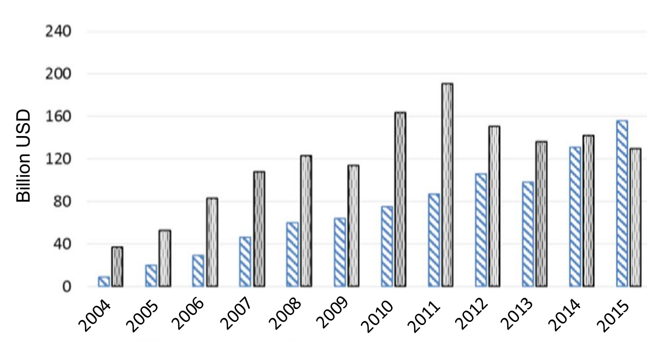

Fig. 4. Developed and developing countries investment in renewable energies [13].

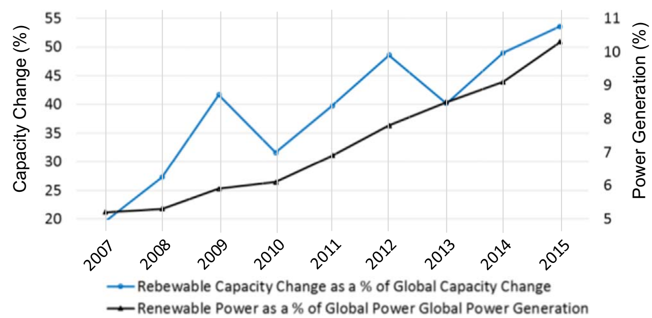

Fig. 5. Renewable Energy Generation and Capacity as a Share of Global Power [13].

relative to the annual GDP [11].

A report made by the Frankfurt school under the UN climate and sustainable energy finance group in 2016, called the global trends in renewable energy investments (GTREI), has been published. The generation capacity of renewable energy and capacity change as a percentage of global power is shown in Fig. 5. There is a linear increase in the share of renewable energy to global power while the capacity change shows an increasing zigzag behavior over the last eight years. However, in the year 2015, a record increment has been observed, as depicted in Fig. 5.

The performance renewable energy investment was noticeably more impressive in the last few years. The capital cost of wind and solar PV has sharply dropped in the last few years. About 103 GW of renewable power capacity (large hydropower excluded), was built in 2015. The capacity was 86 GW in 2013 and 80.5 GW in 2011. The main sources of renewable energy in 2014 were wind and solar, contributing 49 GW and 46 GW respectively. The capacity of wind and solar PV were 32 GW and 40 GW respectively in 2013 [13]. The electricity cost for the renewable energy sources in 2011, considering different studies, publications and technical papers, has been presented in [14]. The presented results compare the US generation prices and residential end-use price for 2014, published by the US energy information administration (EIA). The hydropower has come up as the most competitive renewable technology. The major disadvantage associated with hydropower is the requirement of a suitable site for the location of the plant. On the other hand, renewable energy technologies that can be directly installed and exploited by end-users in the residential areas like geothermal and wind on-shore have reached the grid parity. Other renewable sources like PV in adequate locations are very close to reaching the grid parity.

The potential of different renewable energy sources is immense as compared to the conventional total primary energy supply (TPES) as shown in Fig. 6. It can be observed from the figure that the renewable energy resource with the highest potential is solar energy, considering

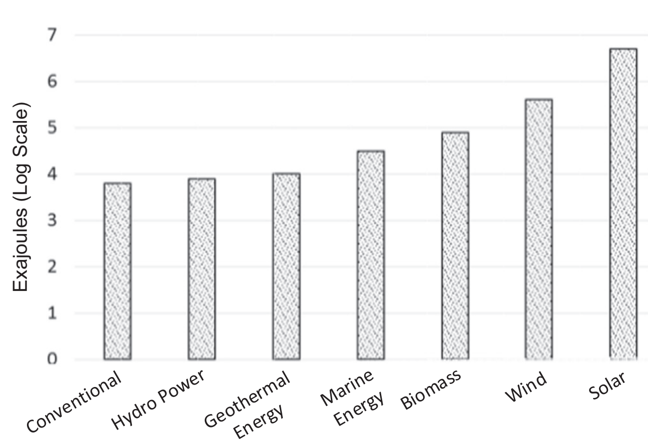

Fig. 6. Global Technical Potential of Different Renewable Energy Sources Compared with Conventional Annual TPES. [2].

Table 1
IRENA Roadmap for Renewable Energy Future 2016 [15].

Sector	Technology	Units	2013/ 2014	Reference Case	REmap
Power	Hydropower	GW	1170	1830	1995
	Wind	GW	370	1070	1990
	Solar PV	GW	175	780	1760
	Bioenergy	GW	95	250	430
	Geothermal	GW	12	42	92
	Ocean	GW	0.5	2	7
	Battery Storage	GWh	130	1580	4000
Transport	Electrical Vehicles	Million Vehicles	0.8	60	160
	2/3 Wheelers	Million Vehicles	200	500	900
	Bio-liquids	Billion Liters	129	250	500
	Bio-methane	Billion m^3	0.01	0.3	0.9
Industry	Bio-energy heat	EJ/yr	8	11	17
	Solar Thermal[3]	GWth	0.1	8	105
	Solar Thermal[4]	Million m^2	1	50	660
	Geothermal	EJ/yr	0.02	0.05	0.4
	Heat Pumps	Million Units	0.2	3	18
Buildings	Bioenergy[1]	EJ/yr	35	21	0
	Bioenergy[2]	EJ/yr	2.5	4	13
	Bioenergy Heat	EJ/yr	4	10	15
	Solar Thermal[4]	Million m^2	534	2020	3230
	Geothermal	EJ/yr	0.3	0.7	0.8
	Heat Pumps	Million Units	4	32	42

only the surface land above the sea level. It can also be observed from the graph that conventional global TPES is lower than the technical potential of all the renewable energy sources [2].

In 2016, a roadmap, named as REmap, has been formulated by the international renewable energy agency (IRENA) for renewable energy future until 2030. IRENA has compiled a reference case based on national plans of 40 different countries. Sector wise technology generation has been listed in Table 1, based on the data of 3013/ 2014, IRENA reference case, and REmap.

3. Emerging renewable and sustainable energy technologies

Renewable energy technologies can be categorized as mainstream energy technologies and emerging energy technologies. Mainstream renewable energy sources comprise of hydropower, wind energy, solar energy, biomass energy, biofuels, and geothermal energy while emerging renewable sources consist of marine energy, concentrated solar photovoltaics, enhanced geothermal energy, cellulosic ethanol, and artificial photosynthesis. There has been a lot of work on the mainstream renewable energy technologies in the past few decades, and it is still going on as in [16–20], which has been discussed in detail in the previous section. Apart from the mainstream energy technologies, some new, renewable energy technologies have also emerged in the last decade and have attracted the researcher community [21–25]. These renewable technologies are still not widely demonstrated or their commercialization level is limited. Many are on the horizon but some have more potential than other renewable energy technologies [26].

The following sections elaborate on only emerging renewable technologies. Different techniques in practice or under development pertaining to the above-mentioned five emerging technologies are discussed: market shares for each technology, the current state of each technology, future prospects, and challenges/drawbacks of each technology are highlighted.

3.1. Marine energy

Marine energy, also known as ocean energy, is one of the very attractive renewable energy sources. Oceans cover about three-quarters of the earth and several techniques have been tested and practiced for extracting energy from these mighty oceans. These techniques consist of wave power (wave energy), tidal power, tidal currents, salinity gradients, and temperature gradients. The major advantage of marine energy as compared to other renewable sources is its consistency and predictability [27]. The potential of only wave energy is comparable to the total of nuclear or hydropower [28].

The energy stored in these vast and powerful oceans in the form of heat, tides, waves, and currents is enough to meet the total worldwide demand of power many times over [29]. However, due to the technological challenges, marine energy contributes only a miniscule proportion of the worldwide energy supply [30]. Different studies have been conducted to analyze the feasibility of selected areas, efficiency of installed technologies, economic aspects of the generated power, and ecological & environmental aspects of these proposed technologies [31–36].

In order to accelerate the implementation of marine energy, several regional government policies have been introduced with various incentives in the past decade [37]. The executive committee of ocean energy systems (OES) has published a report in 2015, where the statistical overview of marine energy in 2015 is highlighted in chapter seven [38]. The installed and consented marine projects' capacity corresponding to the utilized resource based on country as of 2015 is shown in Table 2. It can be observed from Table 2 that tidal power contributes the most energy, followed by tidal currents, while salinity gradient contributes the least, in terms of installed capacity. As per the data of consented projects, tidal power is still on the top and is again followed by tidal currents. Salinity gradient has also shown a remarkable improvement in the consented projects list.

The implementation agreement on OES was initiated by three countries in 2011. The member countries have now (December 2015) increased to 23 [38], as shown in Fig. 7. This rise depicts the increase in interest in developed and developing countries in marine energy.

Several technologies and methods are applied for extracting energy from the oceans. Apart from the offshore wind, which is also one of the mainstream renewable energy sources, there are several other emerging technologies being employed for utilizing marine energy. The five major applied technologies: wave energy (wave power), tidal energy, tidal.

currents, salinity gradients, and ocean thermal energy conversion (OTEC) are discussed in the following sections. Future prospects and challenges along with drawbacks of marine energy are also discussed.

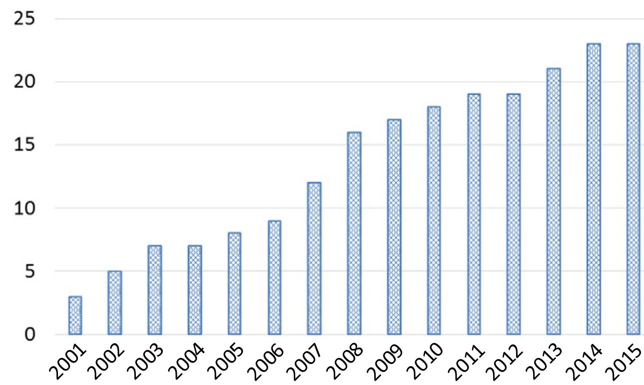

Fig. 7. Yearly membership growth of OES [38].

3.1.1. Wave energy

The source of marine wave energy is wind; as it blows across the ocean, energy transfer takes place. Near the free surface, this energy transfer provides a natural and convenient concentration of wind energy in the water [37]. These waves can transfer energy efficiently and are capable of traveling longer distances with minor losses and some of the waves even gain energy from wind over long open ocean stretches [39]. Wave energy converters transform this energy into electricity. One of the key advantages of wave energy is the spatial concentration of energy in comparison to other renewable energies [40].

Potential for wave energy depends on strength of winds and the temperate latitudes are well suited for the strongest winds i.e. between 40° and 60° north and south on the eastern boundaries of oceans. The theoretical regional potential of wave energy is shown in Fig. 8. The UK is considered the richest country in terms of potential for wave energy.

Wave energy extraction history spans over more than two hundred years. Yoshio Masuda is regarded as the father of modern wave energy conversion technology [40]. His developed navigation buoy powered by wind energy has been commercialized by Japan since 1965 and later by the USA [41]. In 2000, the world's first commercial wave plant was installed on the island of Islay [42]. Wave energy extraction techniques (WEET) can be categorized based on the location and power take-off [40]. Based on location, WEETs can be divided into onshore, offshore, and nearshore types. While based on power take-off, WEETs can be categorized as point absorber, attenuator, oscillating water column, oscillating wave surge converter, submerged pressure differential, and

Table 2
Country-wise Installed and Consented Marine Energy Projects (as per data of 2015) [38].

CountryProjects	Installed Capacity (kW)					Consented Projects (kW)				
	Wave Power	Tidal Power	Salinity Gradient	OTEC	Tidal Currents	Wave Power	Tidal Power	Salinity Gradient	OTEC	Tidal Currents
Belgium						20000				
Canada	9	20000								20450
China	450	4100			170	2760	200			4800
Denmark						50				
France		240000			2500					21618
Italy						99				
Netherlands			50		1300			100000		> 1600
Norway	200									
Portugal	400					5000				
Singapore	16	5								50
South Korea	500	254000		220	1000	500	254000		200	1000
Spain	296									
Sweden	200	8				> 10400				
USA						1545	1350			40
UK	960				2100	40000				96000
All Countries	3031	518113	50	220	7070	69954	255550	100000	200	143958

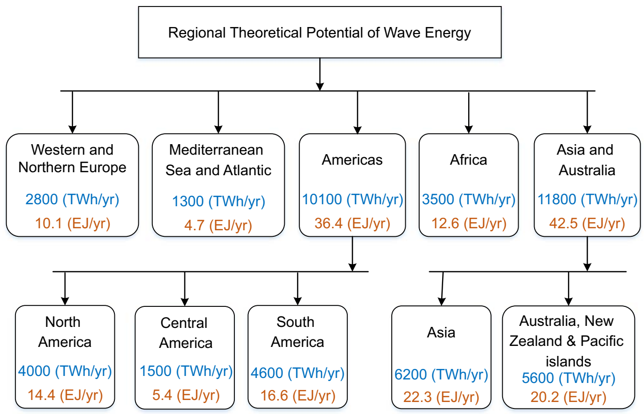

Fig. 8. Regional yearly potential of wave energy [37].

overlapping device etc. [40]. Literature reviews and methodologies pertaining to each of the above-mentioned techniques can be found in [43–50].

3.1.2. Tidal energy

Tidal energy is the result of the rise and fall of ocean waves due to rotational and gravitational forces between the Earth, Sun, and Moon. Tidal behavior is regular and predictable [51]. The first tidal barrages were built across the mouths of estuaries to harness the energy of the tidal flow and were resembling with dams. The magnitude and timing of the tides depend upon global position, the shape of the ocean bed, coriolis acceleration, and geometry of shoreline [37].

The working principle of tidal power plants is similar to the power plants as a reservoir except the wave masses do not flow downhill but move back and forth in accordance with the tidal flow [52]. Tidal energy has been utilized commercially for a long time now. A power station named La Rance tidal power station became operational in 1966 on the Atlantic ocean in the northern France [53].

Tidal energy has an immense potential, even though it is highly location specific. It is estimated that the UK can generate up to 50.2 TW h/yr while Western Europe has a potential of 105.4 TW h/yr [30]. Due to economic constraints, only a fraction of total worldwide potential (500–1000 TW h/yr) is exploited [54].

The turbines used to extract tidal energy from the tides are known as hydrokinetic turbines. These turbines can be categorized as one of the several typical turbine-types; vertical axis turbines, horizontal axis turbines, venture effect turbines, and oscillating hydrofoil as shown in Fig. 9. Further improvement in these technologies can be done by using gears to allow different rotation speeds for the generator and the turbine or making output better through variable frequency generation [37].

3.1.3. Tidal and ocean currents

Tidal current flow is the result of the rise and fall of the tides. These currents are generated due to horizontal movements of water, changed by seabed bathymetry, especially near coasts or other barriers such as islands. The timing and magnitude to tidal currents are highly

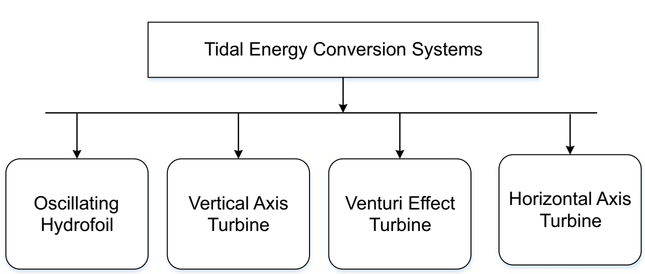

Fig. 9. Major types of Tidal Energy Conversion Devices [37].

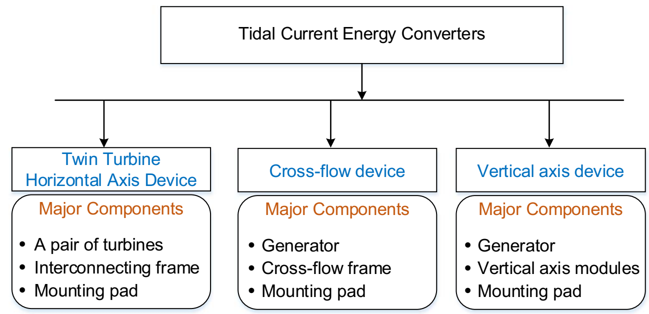

Fig. 10. Major types of TCE Conversion Devices [37].

predictable and largely insensitive to climate change influences [37].

Despite the fact that there are several similarities between the nature of wind and tidal current energy extraction techniques, there are some major differences between the natures of original resources. The energy fluxes of the tidal currents are guarded between the seabed and the sea surface and may be further forced within a channel in contrast to the wind energy [55]. On the other hand, tidal current converters having the same rated power capacity as the wind turbines have the potential to produce four times more energy per year/m^2 [56].

Tidal current energy (TCE) converters are divided into three major types i.e. the twin turbine with horizontal axis device, vertical axis device, and cross flow devices as shown in Fig. 10. Tidal currents are the prospective source to contribute to supply a significant fraction of future electricity [57,58]. A study has been carried out by [56] of 106 possible locations in the EU for tidal turbines. These studies have shown that these sites are capable of generating an estimated power of 50 TW h/yr [56–59].

In addition to the near-shore tidal currents, other significant currents also flow in the oceans. These currents are known as ocean currents [37]. The source of these currents is latitudinal disturbances of winds and thermohaline ocean circulation. The rate of the ocean currents is slower but more consistent compared to the tidal.

currents. Ocean currents are unidirectional while tidal currents change direction with flood and ebb cycles [51].

The basic principle of capturing the energy from open-ocean currents is similar to the tidal current energy extraction but some of the infrastructure involved will differ. Neutrally buoyant turbines with mooring lines and anchor systems may be more suitable for deep-water applications [37]. Generators used for tidal currents need to generate energy in both directions while open-ocean turbines do not require this feature. The southeast national marine renewable energy center (SNMREC) in the US at Florida Atlantic university is intended to recover energy from ocean currents by advancing the science and technology relate to this field. Especially from the Florida current being a part of the gulf stream system found offshore from the center [51].

3.1.4. Salinity gradient

The energy created from the difference in salt concentration between two liquids is known as salinity gradient power. There are two modes of operation of the energy extraction process. These are standalone (power plant is located at the junction of sea and river) and hybrid energy generation process. Hybrid processes focus on the enrgy production process i.e. desalination or a wastewater treatment [60].

The energy associated with a salinity gradient can be harnessed using pressure-retarded osmosis, reversed electro dialysis (RED) and other associated energy technologies in the standalone process. The purpose of these technologies is to harness the chemical potential between freshwater and seawater, also known as osmotic power. This potential is captured as a pressure across a semi-permeable membrane. [37]. The most suitable location for this pressure is the mouth of the rivers, being the junction of fresh and seawater.

Recently the technical potential for power generation through salinity gradient or osmosis was calculated as 1650 TW h/yr. The major issue associated with energy extraction through osmosis is cost-effective technologies. The prototype of first osmotic power plant became operational at Tofte, near Oslo in Norway in 2009 [61,62].

The reversed electro dialysis process binds the difference in chemical potential between the two solutions. By using an alternate series of cation and anion exchange, concentrated salt and freshwater are brought into contact. A voltage is generated across each membrane due to the chemical potential difference. The total potential of the system can be calculated by summing the potential of individual membranes [61].

The process of exploiting chemical potential was proposed and used in the 1970s for the first time and is known as pressure-retarded osmosis (PRO) or osmotic power [62]. In PRO process, the variation in the salt concentration between two liquids (seawater and freshwater) is used. This process is also known as natural osmosis. There is a strong tendency in the seawater and freshwater to get mixed and this tendency will remain as long as the pressure difference between the two liquids is not greater than the osmotic pressure difference.

The amount of salinity gradient energy available globally is estimated at 3.1 TW [64]. The theoretical amount has to be adjusted for technical feasibility and environmental impacts. The theoretical and technical potential for different regions is shown in Fig. 11.

3.1.5. Ocean thermal energy conversion

The source of OTEC is solar energy; when the sun's rays fall on the oceans, thermal energy is absorbed and stored in the upper layer. The energy is extracted by making use of OTEC cycle [65]. OTEC cycles use the temperature difference between the warm seawater at the surface of the ocean and the cold seawater (between an 800–1000 m depth) to produce electricity. Warm seawater is used to produce vapors (working fluid for driving a turbine) while cold water is used to condense the vapors and ensure there is enough vapor pressure difference to drive the turbine [66].

Three major techniques utilized for extracting energy by the OTEC plants are open-cycle, closed-cycle, and hybrid-cycle [67]. Open cycle uses seawater as the working fluid, while closed cycle OTEC uses ammonia, chlorofluorocarbon (CFC) or propane as the working fluid. Hybrid conversion cycles utilize a combination of open and closed cycle schemes [37].

Although there is a slight seasonal variation in the temperature gradient, the OTEC resource can be catered as a continuously available power resource. Theoretical potential of OTEC is considered highest among different sources of ocean energy [67]. In order to operate a commercial-scale power plant based on OTEC, a minimum temperature difference of 20 °C is required. The annual average temperature difference contours from 20 °C to 24 °C between warm surface seawater and cold seawater at a depth of 1000 m is shown in Fig. 12 [51].

OTEC has the potential of generating approximately all of the current global energy demand (10 TW) without affecting the thermal

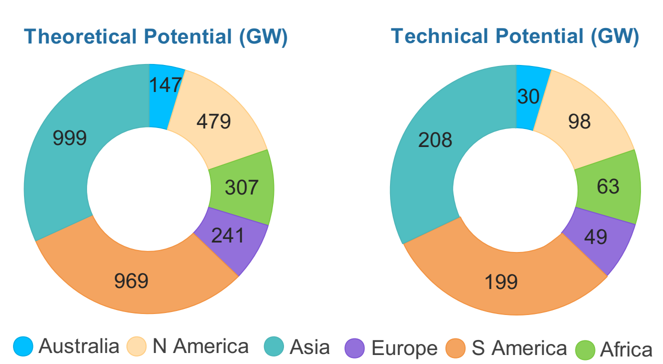

Fig. 11. Theoretical and technical potential of Salinity Gradient for different Continents [63].

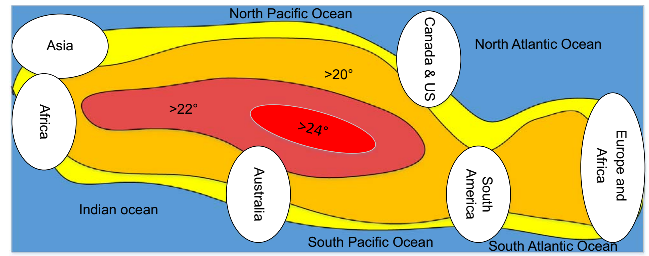

Fig. 12. Contours of annual average temperature difference, from 20 °C (Yellow) to 24 °C (Red) [51].

structure of oceans [68]. OTECs find their major demand in small islands, which need both power and fresh water, while currently, per unit cost is the major hurdle in making the OTEC commercial.

3.1.6. Future prospects, challenges, and drawbacks

There are several frontiers, which need to be addressed for using the ocean's energy and making it a key contributor in world energy in future. Major issues to be addressed are related to technical, economic, social and environmental, and infrastructural areas.

Technical challenges include the issues related to the resources, devices, and array configurations. These issues need to be addressed to use ocean energy in large scale. The technical issues related to the ocean thermal energy conversion, salinity gradient, and ocean current technologies should be addressed in priority. Among ocean energy extraction techniques, these are the least mature technologies.

It is the obvious obligation of the policymakers and utilities to adopt those technologies, which have minimum risk and cost. The most significant barrier for making marine renewable energy technologies commercial is the high cost. The per-unit cost of energy produced by marine energy technologies is higher relative to other renewables.

The life of ocean energy is long, more than 25 years in general and over 100 years for tidal barrages [37], the long-term effect of ocean energy technology is a major consideration. The commercial-scale deployment of ocean energy may result in environmental and social issues, which have not been considered in laboratory or pilot stage testing, particularly for tidal range systems [37].

The infrastructural challenges related to the ocean energy can be divided into two major types relating to grid issues and the supply chain. In order to integrate the ocean energy into wider energy networks, the characteristics of the widely distributed energy sources and their major sources should be recognized and catered.

Although marine energy has a huge potential to provide sustainable energy to fulfill the energy demands but there are some drawbacks of marine energy also. Marine life may be harmed/displaced or it may harm the habitat of marine life negatively. Due to the presence of marine energy extracting devices (firms), the size of the shipping channel and opportunities for recreation may reduce. The equipment may get corrode frequently and sea storms may damage it due to the exposure to strong ocean waves.

3.2. Concentrated solar power/photovoltaics

The technology used for generating electricity using heat produced by solar irradiation by concentrating it on a small area is known as CSP technology. CSP technology make use of mirrors or lenses to reflect sunlight into a receiver where a primary circuit (thermal energy carrier) collects the heat, and it is either used directly or via a secondary circuit to generate electricity by utilizing a turbine [69]. CSP equipped with a heat storage system is capable of generating electricity in cloudy skies and after sunset. As compared with wind and photovoltaics, CSP with thermal storage ensures a significantly higher capacity factor and dispatchability [70].

The solar energy collector is a major component in each CSP

Table 3
The four CSP technologies based on RT and FT. [70].

Receiver Focus Type	Mobile	Fixed
Linear Focus	Parabolic Trough	Linear Fresnel Reflectors
Point Focus	Parabolic Dishes	Solar Towers

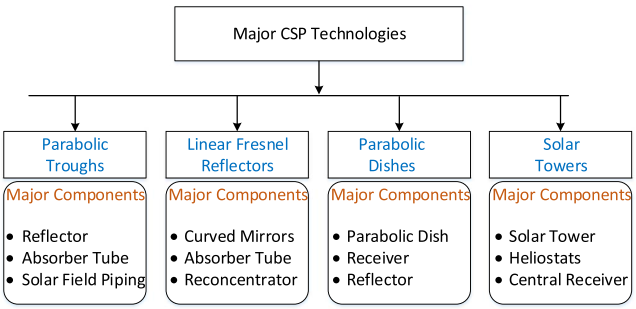

Fig. 13. Components of the four major CSP Technologies [70].

technology. The solar collector is responsible for the transformation of solar radiation into heat energy. It absorbs the incident solar radiation and transforms it into heat. The heat energy is then carried away by a heat transfer fluid (HTF), flowing through the collector. HFT is responsible for linking the collector and the power generation system [60]. Based on the technology used for collecting sun rays (collector type), CSPs are categorized into four major types. These four types are categorized based on the way they focus the sun's rays (FT) and the technology utilized to receive the sun's rays (RT) as shown in Table 3 and Fig. 13.

To reach the temperature required for generating electricity through CSP technologies, an abundance of direct solar radiations is needed. This makes CSP limited to hot and dry regions only. There are various regions in the world, which are suitable for CSP technologies, though [71]. These regions include the Middle East, North Africa, South Africa, Australia, the Western US, and some parts of South America.

The majority of project based on CSP technologies, which are currently under development or construction, are based on the parabolic trough technology. It is considered as the most mature technology and gives the lowest risk in terms of development. There is significant potential to reduce the capital costs and performance improvements in solar tower.

and Fresnel systems, as these technologies are in their initial stages of developments [72].

The first CSP power plant without thermal storage was built in California, US between 1984 and 1991 [73]. The interest in CSP resumed in the 2000s after a long period of stagnation due to low-cost fossil fuels energy. Spain and the USA are the main stakeholders in the field of CSP technologies. The CSP installed globally amounted to 2 GW in 2012 with an addition of 15–20 GW under construction or planned, mostly in the USA and Spain. CSP plants are in operation, under construction or planned in many of the Sun Belt countries [74].

Extensive explorations have been carried out regarding various solar collector types, materials, and structures, and a multitude of heat transport, storage and electricity conversion systems has been tested [75–81]. Every aspect of CSP that has made progress, especially in the last decade, was geared towards expanding the efficiency of solar-to-electric power production while making the economic aspect in comparison with fossil fuel derived power [82]. Details of all the four major CSP technologies are tabulated in Table 4.

In order to assure regular production and guarantee the required capacity, all CSP plants with or without storage, are equipped with fuel-powered backup systems. Energy to the heat transfer fluids or liquids is provided by the fuel burners; fossil fuels, biogas or solar fuels. Fuel

Table 4
Description of the four major CSP technologies. [73,74].

Technologies Parameters	Parabolic Trough	Linear Fresnel Receiver	Solar Tower	Parabolic Dish
Annual Efficiency[a]	15%	8–10%	20–35%	25–30%
Hybrid Mode Possibility	Yes	Yes	Yes	Limited Cases
Water Cooling (L/MWh)	300 or Dry	300 or Dry	200 or Dry	None
Solar Fuels	No	No	Yes	Yes
Land Occupancy	Large	Large	Medium	Small
Storage Possibility	Yes[b]	Yes[b]	Yes[c]	Yes[c]

[a] Solar to electrical conversion.
[b] Not with DSG.
[c] Depends on plant configuration.

powered backups make it possible to almost completely guarantee the production capacity of plants at a lower cost than if the plant only depended on the solar field and thermal storage [70]. This storage and the backup capabilities make CSP capable of benefiting electrical grids significantly. The thermal storage technologies utilized by CSP are more effective and less costly due to lesser thermal storage cycle losses as compared to other energy storage technologies.

Due to various unique and significant advantages of CSP, on-demand energy can be generated by combining CSP technologies with thermal storage, and integration with conventional energy sources in hybrid mode can improve the performance of both. This aspect can gain the attention of researchers and energy sector industries. A report on region wise production and consumption of CSP-based electricity (in TW h) by 2050 has been published in [71], and is also summarized in Fig. 14.

Currently, CSP technologies are not deployed widely. Between 1985 and 1991, only a total of 345 MW capacity were installed in California and have been operational since then. Interest in CSP has been growing over the past decades. Several new CSP plants have been brought on line since 2006, due to the declining investment costs and leveled cost of electricity generation (LCOE) [72].

Spain is now considered the largest producer of CSP electricity. Apart from that, several projects in the USA and North Africa are either in the planning phase or under construction phase. This increased interest in CSP technologies has resulted in an addition of several new power plants. A report on newly added CSP power has been published by [70] and is also shown in Fig. 15, the additional CSP added in 2013 vs CSP capacity by the end of 2012. Details about the different technologies used in CSP are given in the following section.

3.2.1. Parabolic trough (PT)

In PT technology, sun rays are concentrated on heat receivers that

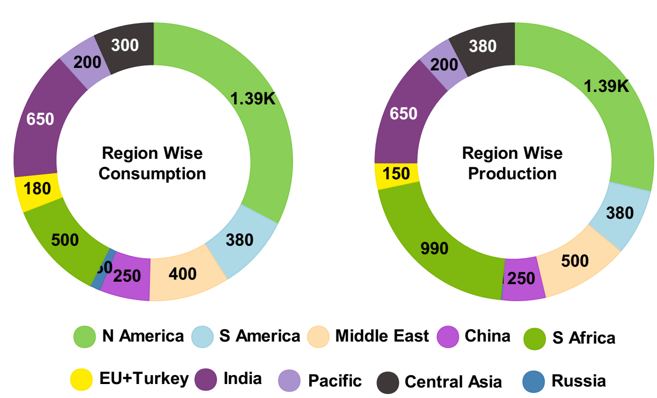

Fig. 14. Production and Consumption Estimation of CSP-based Electricity by 2050. [70].

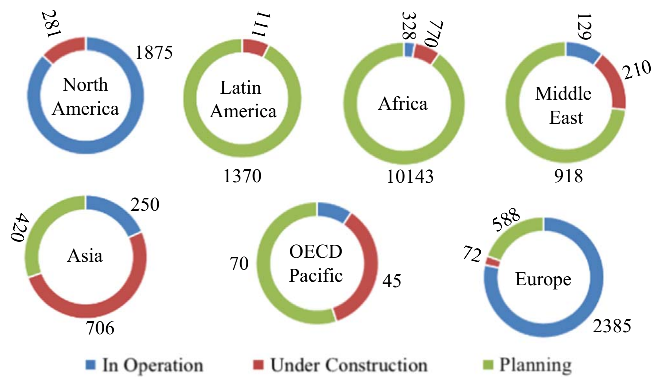

Fig. 15. Additional CSP added in 2013 vs CSP Capacity by the end of 2012. [70].

are placed on the focal line with parabolic mirrors. The receivers are coated with a special coating to reduce the infrared re-irradiation and increase the energy absorption. Convection heat losses are avoided by placing the receivers in an evacuate envelope of glass. A heat transfer liquid (synthetic oil or molten salt) is used to remove heat and is transferred to a steam generator to produce superheated steam. The superheated steam is used to run the turbine and generate electricity [71]. The water is returned to the heat condensers after being cooled and condensed. In order to generate electricity at times when the sun is not shining, heat from the heated fluid in PT can also be stored in thermal storage systems [83,84].

The total capacity of PTs installed up to date is about 850 MW. Typical PT plants range from 14 to 80 MW and are mainly located in Spain and the US [71]. The major advantages associated with PT are that PTs use the most mature and commercially viable CSP technology, commercially proven net plant efficiency of about 15%, modular systems, storage capability, and commercially proven investment costs, hybrid concept, operating costs and land-use factor. Some of the major disadvantages associated with the PT technology are high thermal losses, lack of an ideal medium for heat transfer and long length pipes running between the array and the steam generating plant.

3.2.2. Linear fresnel reflectors (LFR)

LFR collectors are similar to PT collectors but LFR uses a series of long flat and slightly curved mirrors. These mirrors are positioned at different angles so that the sunlight could be directed to either side of a fixed receiver. The fixed receiver is located some meters above the main mirrors field. In order concentrate the sunlight on a fixed receiver, a single axis tracking system is installed at each mirror line and is optimized individually. Astigmatism may distort the focal line of LFR collectors, unlike PT collectors. A secondary reflector is used to refocus the rays that are missing any tubes [72]. A more recent LFR technology, known as compact linear Fresnel reflectors (CLFRs), uses two equivalent receivers for every row of mirrors to minimize the land usage and then uses a parabolic trough to produce a given output [85].

There are three LFR plants, which are operational, up to date and all of these three plants have been operational since 2008. These plants are located in California, USA, New South Wales, Australia and Murcia, Spain. The capacity of these plants is 5 MW, 4 MW, and 1.4 MW, respectively [71]. Some of the major advantages of LFR technology are readily available materials, lower manufacturing and installation costs as compared with parabolic troughs, the system can generate steam directly as they use water as heat transfer liquid, hybrid operations possible, and have lower heat transmission losses. Some of the disadvantages associated with LFR are performance, investment and operation costs are not yet commercially proven, solar to electric efficiency is 8–10%, which is lesser than that of PT, combine with thermal storage is complex.

3.2.3. Parabolic dishes (PD)

Parabolic dish collectors (PDC), also known as a solar dish collector, is the CSP technology in which sun rays are concentrated at a focal point supported above the center of the dish. Both the dish and receiver track the sun by moving in the tandem [74]. The receiver in PD may be a Stirling engine or a microturbine. Due to this design, there is no need for a heat transfer liquid and cooling water in PD based technologies, which results in a larger heat to electricity conversion ratio. It is claimed that large-scale production of PDs will allow them to compete with larger solar thermal systems [86]. Several 10 kW systems in Europe, few kW project in the USA are under development phase and a 100 MW project is under consideration in Australia.

Dish systems still require much more development, though; the current energy cost of dish technologies is almost twice that of parabolic trough systems. Major advantages associated with this technology are more than 30% conversion efficiency, no need for cooling, well suited for remote and stand-alone operations, modular system, not restricted to flat terrains, easy to manufacture, and mass production ease due to the use of existing parts. Some of the disadvantages of this technology are an absence of large-scale commercial plants, lack of commercially proven investments, performance and operation costs, and difficulty in grid-connection operation.

3.2.4. Solar towers (ST)

In ST technology various computer-assisted mirrors also known as heliostats track the sun separately over two axes. These mirrors concentrate the solar energy onto a single receiver. The receiver is mounted on the top of the central tower where a thermodynamic cycle is driven by heat and thus produces electricity [72]. The concentration of ST is higher compared to other CSP technologies. Water steam, synthetic oil or molten salts are among the main heat transfer fluids used by ST. The working temperature can range from 250° to as high as 1000° depending on the receiver design and the working fluid.

STs are on the verge of commercialization. In the 1980s and 1990s, two 10 MW power plants were deployed in California, USA. Both of these since have been decommissioned and recently various projects are under development phase is Spain, the USA, Germany, and Israel [84]. The major advantages associated with the technology are higher mid-term efficiencies due to the potential for achieving higher temperatures, better suited for dry cooling than a parabolic trough, and easy to install on hilly sites. The major disadvantages with this technology are due to lack of commercial availability, commercially proven operation, investment costs, and performance is not proven yet.

3.2.5. Future prospects, challenges, and drawbacks

The total capacity of CSP in Europe could grow to 30 GW, 50 GW in North America, 23 GW in the Middle East and Africa by 2020, and it could rise to 337 GW by 2030 [84]. In order to make CSP a competitive source of power in future, various frontiers like storage technologies, power blocks, cooling of CSP plant, transmission medium of heat and electricity, and the cost of CSP need to be addressed, though all these areas have enormous potential for advancements.

The major areas to be considered for improvement in PTs and LFRs include solar field elements; the thick glass sheet could be replaced by another cheap material, replacement of costly heat transfer liquids with cheap liquids, a direct steam generator for PT could increase the working temperature and ultimately increase the efficiency. The major frontiers which need attention from developers in PD and ST technologies include the water cooling in plants can be replaced by other mature technologies used in fossil fuels, which will increase the heat to power conversion ratio. Atmospheric air can also be used as a heat transfer medium in these high temperature based technologies, which will reduce the cost and pressurized heat that can be directly sent to a gas turbine to generate electricity.

Despite the enormous potential and various benefits of the CSP technologies, there are some drawbacks also which are associated with these technologies. CSP technologies require a considerable amount of land due to the requirement of high-intensity reflections targeted to receivers, which are faraway from the reflectors. CSP technologies are very location specific and are usually installed far away from the energy consumption areas. Therefore, they may face high transmission/ distribution losses. The performance of CSP technologies degrades significantly for diffused irradiations.

3.3. Enhanced geothermal energy

Geothermal energy is the form of thermal energy stored in the earth's crust. The origin of geothermal energy from the earth's crust is from two major sources: 20% from the original formation of planet earth and 80% from the radioactive decay of earth materials [87]. The temperature difference between the core of the earth and its surface is known as geothermal gradient, and it drives a continuous conduction of thermal energy from the core to the surface in the form of heat. There is mostly water with different amounts of salts and minerals dissolved in it. The potential of geothermal energy is at par with other mainstream renewable energy technologies. A comparison between wind, solar, hydro, and geothermal energy has been presented in [88]. Comparison between initial investment cost and payback time of all the major mainstream renewables technologies is shown in Fig. 16.

The traditional approach of exploiting geothermal energy is to find the naturally occurring reservoirs of superheated steam and hot water. Regional and local tectonic and geological phenomena play a vital role in the sustainability of these naturally occurring reservoirs. Due to these factors, conventional geothermal energy techniques are only restricted to those regions which are rich in natural reservoirs. In order to overcome these limitations, an enhanced version of geothermal energy has been introduced, known as EGS. This paper will only discuss EGS technologies and their potentials.

EGS, which is also known as engineered geothermal energy (EGE) or hot dry rock (HDR) energy, does not depend on the occurrence of natural geothermal reservoirs. The reservoirs for extracting the geothermal energy are enhanced or engineered in the EGS approach. This makes EGS adaptable in more areas and especially in those regions, which lack in natural reservoirs. The major advantages associated with EGS over conventional geothermal techniques are extended lifetime, increased productivity, siting flexibility, expanded resources, sizing flexibility, and above all environmental advantages.

A complex set of parameters controls the performance of EGS power plants. These parameters include a reservoir, geological conditions, drilling of a well, and well completion. In order to extract thermal energy, it is required to drill to depths where the rock temperature is sufficient enough to justify the investments. The first step in building a power plant based on EGS technology is to develop an EGS reservoir in the designated region. There are various steps in developing an EGS reservoir. A report has been formulated by [89] for developing EGS reservoirs and to extract geothermal heat energy for a generation for electricity. The major five steps proposed by the author for the development of an EGS reservoir are as follows. Step three is

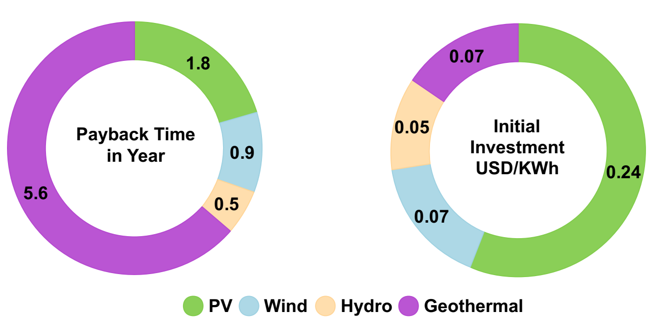

Fig. 16. Comparison between initial investment cost and payback time of mainstream renewables technologies. [88].

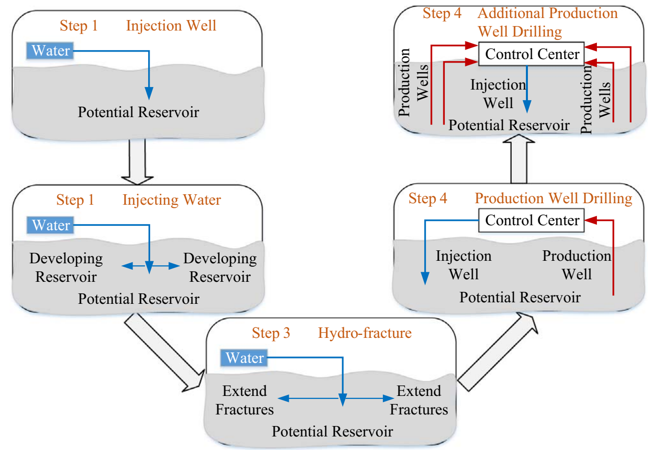

Fig. 17. Steps for the development of an EGS Reservoir [89].

considered the most crucial step in the development of an EGS reservoir.

- An injection well is drilled into hot basement rock that has limited permeability and fluid content.
- Water at a specific pressure is injected to ensure fracturing or to re-open existing fractures.
- After fracturing or opening existing fractures, water is continuously pumped to extend fractures and re-open old fractures in the hot basement rock.
- A production well is drilled to intersect the stimulated fracture system and to circulate water to extract heat from the hot basement rock.
- Finally, additional production wells are drilled to extract heat from large volumes hot basement rock to meet the requirements of power generation.

Fig. 17 shows the pictorial view of the steps involved in the development of an EGS reservoir.

Geothermal energy is considered one of the few renewable energy technologies, which can be employed as the base load power-generating source. The quality of geothermal energy is based on the function of temperature gradient and depth of the well along with the natural porosity. Good locations are over deep gradient by a thick 3–5 km loss. A report was published by MIT in 2006 on EGS technologies and it has been claimed in the report that it layer of insulating.

sediments, which slow down the heat would be affordable to generate 100 GW or more of electricity by 2050 with EGS technology. The EGS reservoirs are categorized into shallow, mid-range and deep wells, based on the reservoirs depth. A comparison between the budget requirements for each type of well in case of EGS and oil and gas (O & G) has been compared by [90] and a summary is shown in Table 5.

Table 5
Cost comparison of EGS and O & G reservoir. [90].

Well Depth (m)	Well Category	EGS Estimated cost (Million USD)	O & G Estimated cost (Million USD)
1500	Shallow	2.303	0.9
2500		3.371	1.81
3000		4.022	2.55
4000	Mid -range	5.223	5.1
5000		6.740	6.45
6000	Deep	9.172	8.92
7500		14.645	13.83

Various aspects of enhanced geothermal energy have been addressed in [91–95]. These aspects include geothermal resource base assessment, recoverable EGS estimates, review of EGS related technologies and their current status, issues in designing subsurface systems, economics of drilling technologies, issues in energy conversion systems associated with EGS, environmental impacts and feasibility criteria, and economic analysis of the EGS projects and their sustainability [96–98].

The resource base of EGS is huge but it is not distributed evenly. In active tectonic regions, a temperature of more than 150 °C at the depths of less than 6 km is more common but it is not confined to those resources [99]. There are areas in every region with more favorable conditions than others. The highest temperature regions areas are more favorable where the flow of heat is high, thermal conductivity is low and local situations are favorable. Among the favorable regions, only a portion of EGS will be accessible due to various local limitation like urban areas, major roads, utility corridors, national and state parks, wilderness regions, and national monuments etc [100].

The worldwide effort history to extract the heat energy from the rocks that do not have naturally high permeability began with the Fenton hill hot dry rock experiments in the US in the 1970s [101]. Later in other countries like the UK, France, Germany and Japan also have joined the project. After completing that project, several other projects were also developed, including the Rosemanowes, Hijiori, Ogachi and Soultz projects. The aim of these projects was to further develop the idea of creating a reservoir in crystalline rock in other physical settings. These field experiments took place in the UK in 1975 and then later in other various countries like France, Sweden, Germany, and Japan [102,103].

The energy conversion systems utilized in EGS are mainly derived from the conventional geothermal energy systems with some appropriate changes. In some cases, ideas are borrowed from the fossil-fuel energy conversion systems to handle those special issues that may be faced due to EGS fluids. The use of CO2 as the heat transfer medium in EGS may cause various issues. These issues have been discussed, and several feasible solutions have been presented by different researchers [104–106].

There are some potential environmental impacts from the geothermal power development. These impacts include gaseous emission water pollution, land usage, induced seismicity, water use and induced landslides etc. Despite these potential impacts of geothermal energy, current and long-term geothermal energy technologies generally, present much lower environmental hazards as compared to conventional fossil-fueled and nuclear power plants [91]. However, there are certain factors that must be considered before deploying an EGS energy power plant. These factors are usually associated with usage of ground water and its contamination, induced seismicity and land subsidence. Issues related to air pollution, noise and safety also merit consideration.

There are some fundamental differences between the EGS technologies and the hydrothermal systems. EGS technologies provide means for mining heat by designing and stimulating a reservoir from a portion of universally present stored thermal energy in rocks at desired depths. The characteristics of the reservoir would be similar to a commercial hydrothermal system. Various energy conversion systems are used for converting the geothermal energy into electrical energy. The major conversion systems used for EGS are binary recuperators, single flash and triple expansion etc. A comparison between all these technologies in accordance with working fluid and operating temperature are shown in Table 6. Country-wise different EGS projects along with their capacities are tabulated in Table 7.

The EGS techniques for extracting heat from geothermal energy to generate renewable and sustainable energy can be categorized into the following types.

- Enhancement of conventional geothermal systems by flushing extra fluid through a hydrothermal system in addition to the naturally available ground water.
- Stimulations to create additional permeability, all the way down to the HDR. This technique is applied to the places where there is no potential for geothermal energy except the pumping of fluid at those depths.

3.3.1. Future prospects, challenges, and drawbacks

There are three critical assumptions, which are normally made during the modeling of EGS technologies. These three assumptions need thorough evaluation and testing apart from the economic viability of EGS power plants. The first one is a demonstration of a commercial-scale reservoir, which is required to minimize temperature decline in the reservoir. Second is sustained reservoir production. It has been proved through various research activities that 200 °C fluids flowing at 80 kg/s are needed for the economic viability of an EGS based power plant. But up till now, no EGS project has attained flow rates more than 25 kg/s. The last parameter is the replication of EGS reservoir performance. Up till now, EGS has not been proven to work over a range of sites at a commercial level with different geological properties [93].

It can be concluded that a sound investment in R & D and a pre-emptive level of engagement in the next decade could make EGS a major contributor in supplying pollution free energy for utilities. This will ultimately reduce the consumption of fossil fuels and other environmentally hazardous energy technologies.

Enhanced geothermal technologies have a huge potential to mitigate the carbon emissions and are sustainable. However, there are some drawbacks of these technologies also. The EGS may result in small earthquakesor landslides in the areas being engineered for developing wells. EGS may cause minor environmental issues (air and water quality) especially if the plants are not properly designed and/or maintained. EGS is also very location specific and siting of potential sites results in heavy upfront costs.

3.4. Cellulosic ethanol

Ethanol belongs to the alcohol family and can be produced from a variety of plant materials as feedstock. This is used as liquid fuel in motor vehicles. The two major sources for producing ethanol are sugarcane and corn starch. The main problem associated with these techniques is that both of the above-mentioned raw materials are edible and are used by human beings as food ingredients. Apart from these conventional methods of producing ethanol using edible raw materials, there are some emerging technologies, which use wood, grass or other inedible parts or remnants of plants. All these emerging technologies make use of the plant cellulose to generate ethanol. The ethanol produced by processing cellulose is known as cellulosic ethanol.

The process of making cellulosic ethanol is complicated as compared to the process of producing ethanol from the sugarcane or cornstarch [107]. It has been estimated by the researchers at the university of California at Berkeley that on a life-cycle basis, cellulosic ethanol has the potential of lowering greenhouse gasses emission by 90%, relative to the conventional petroleum-based gasoline [108]. Some other analysis has shown that cellulosic ethanol produced from certain feedstock could be carbon negative. That means during the whole life cycle process of cellulosic ethanol more carbon dioxide will be removed from the atmosphere as compared to the CO_2 being emitted into the air.

Biofuels are categorized as first, second, and third generation biofuels. Oil, sugar, and starch are the first-generation biofuels, and these are easily convertible to ethanol, diesel, and butanol using conventional conversion technologies. Cellulosic ethanol is considered second-generation biofuel and is made from lingo-cellulosic biomasses,

Table 6
Comparison of EGS Energy Conversion Systems [92].

Geo-fluid Temp (°C)	Energy Conversion System	Typical Application	Working Fluid	Cooling System
100	Basic Binary	O & G Waters	R-134a	Water (Evaporative Condenser)
150	Binary/Recuperator	O & G Waters	Isobutane	Air
200	Binary or Single Flash	EGS	Isobutane or Geo-fluid	Air or Water
250	Double Flash	EGS	Geo-fluid	Water
400	Single or Triple Expansion	Supercritical EGS	Geo-fluid	Water

Table 7
Country-wise EGS Energy projects with capacity [90].

Country	Project Type	Capacity (MW)	Plant Type	Depth (km)
France	R & D	1.5	Binary	4.2
USA	R & D	1–50	Binary	unknown
	Demonstration	unknown	Flash	6
Germany	Commercial	3	Binary	3.3
Australia	Commercial	7–30	Binary	4.1
	Commercial	250–500	Kalina	4.3
Japan	R & D	unknown	Flash	1.1
UK	Commercial	10	Binary	4.5
	Commercial	3	Binary	4.5

which include agricultural residues and dedicated energy crops. The conversion process of these second-

generation biofuels is more complex. The third-generation biofuels are called 'drop-in' fuels and are similar to petroleum in composition and fuel value. These are produced from various sustainable sources such as cellulose, municipal waste or algae. There are several ways for making cellulosic ethanol, which is also known as lingo-cellulose ethanol. The two major processes that have the potential for extraction of cellulosic ethanol by the researchers are cellulolysis and gasification.

There is virtually no commercial-scale production of ethanol from cellulose, but various researches have been taken and are considered as the next generation of energy from ethanol [109–111]. There are four main sources of feedstock for cellulose. First, one is wood residue, and it comes from the wood industry, saw, and paper mills, and furniture manufacturing. Second is agriculture, and it comes from residues of straw, corn stover, husks, and bagasse. The third source is dedicated energy crops, and these include herbaceous, woody crops, and tall grasses. The final source is municipal solid wastes, which include paper and other cellulosic material [112]. An analysis of the theoretical yield from various feedstocks is shown in Fig. 18. Fig. 18 shows the theoretical yield of each mentioned feedstock against gallon per ton

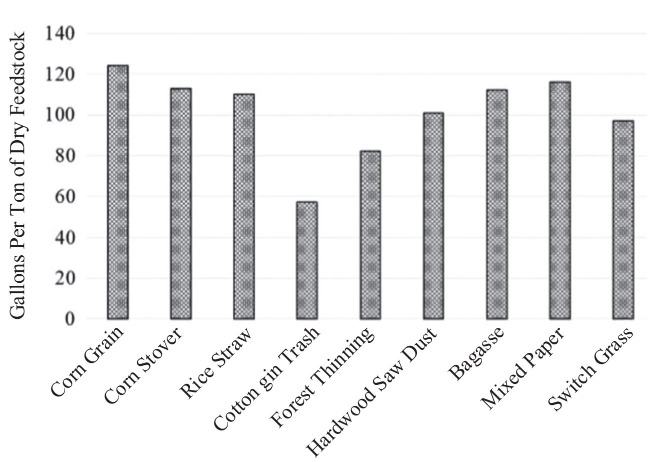

Fig. 18. Theoretical ethanol yield of dry feedstock [112].

of dry feedstock.

3.4.1. Cellulolysis (biological approach)

The process of formation of the cellulosic ethanol is more complex compared to the conventional processing of starch or grain. Before doing the process of hydrolysis in cellulosic ethanol formation, a process called pre-treatment is required; and before the pre-treatment, biomass goes through a step called size reduction where the size of biomass is compacted to enhance the efficiency of the conversion process and to make it easy to handle. This may be the grinding of agricultural products or chipping of wood to make them uniform in size. A detailed description of all the involved steps is shown in Fig. 19 and is explained as follows.

- In pretreatment, the hemicellulose fraction from the biomass is broken down into simple sugars. These are normally five or six carbon soluble sugars.
- In hydrolysis, the remaining cellulose is hydrolyzed into glucose. This step is also known as saccharification as it produces sugars.
- During the fermentation process, the glucose is converted into ethanol. This reaction is caused by yeast or bacteria, which feed on the sugars.
- After glucose and pentose fermentation, the ethanol is separated from other components. A final dehydration step is used to remove the residual water from the ethanol.
- The electricity required for ethanol production can be generated from lignin and other by-products, which are produced during the biomass to ethanol conversion. Lignin, in fact, produces more energy than required for the process of cellulolysis.

3.4.2. Gasification (thermochemical approach)

The gasification process does not break the cellulose into sugar molecules; instead, it converts the carbon in the raw material to a synthetic gas. It uses partial combustion to accomplish the task. A specific kind of fermenter is then fed with the produced carbon dioxide, carbon monoxide, and hydrogen. It uses another microorganism instead of bacteria for the fermentation process. The microorganism, named Clostridium, will ingest the produced gasses and produce ethanol and water. The process can be broken down into three major steps. Each of the steps is shown in a block diagram in Fig. 20 and is explained in detail in the following paragraph.

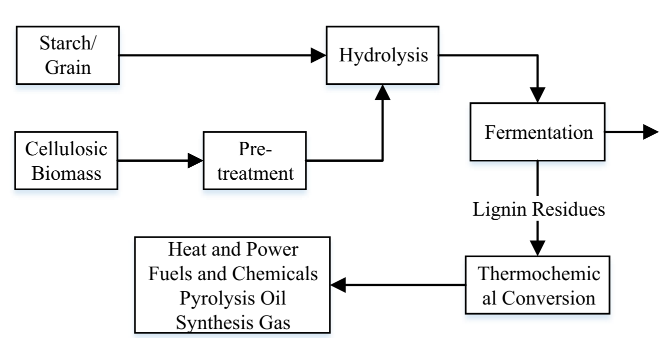

Fig. 19. Block diagram for Cellulolysis process [113].

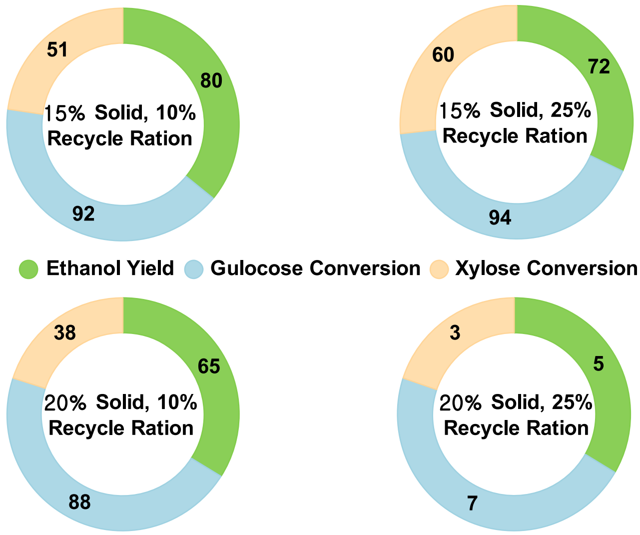

Fig. 20. Block diagram for Gasification process [114].

- The purpose of the gasification process is to break down the complex carbon-based molecules to get CO_2, CO, and H_2 gas.
- The fermentation process converts the produced gasses into ethanol and water by using the microorganism, Clostridium.
- The final step is the desalination. During this process, the produced ethanol is separated from the water.

Some other microorganisms are also being tested for enhancing the efficiency of the conversion process and another family of the same microbe has been discovered with double the efficiency as compared to the above stated.

The history of ethanol and ethanol-gasoline is quite old. Henry Ford in late 1800s equipped his model T as a flexible fuel vehicle i.e. it can use alcohol, gasoline or a mix of gasohol as the fuel [113,114]. Demand for gasoline decreased after world war 1. However, during the war, its demand peaked. The decrease in demand for ethanol after the war was due to gasoline being used as motor fuel [115,116].

One of the integration challenges in the processing of cellulosic ethanol is managing the properties of high-solid mixtures. Adding water to the biomass mixture makes it thicker and viscous. However, this has vital consequences for the conversion and efficient flow of the biomass, through the unified process [117,118]. In order to define the best ways to cope up with high-solids, the biomass unique capabilities based rheology methods have been proposed in [117]. It has been shown in the research that the ethanol yield is falling vividly at moderately high solids meditation and at a high recycle ratio [117]. This has also been depicted in Fig. 21 by making variations in both the solid concentration and recycle ratio. Effects on the yield of ethanol, glucose, and xylose have been compared to the two variables mentioned above.

Several researches have been conducted by researchers for estimating the cost of producing ethanol from cellulosic materials. The

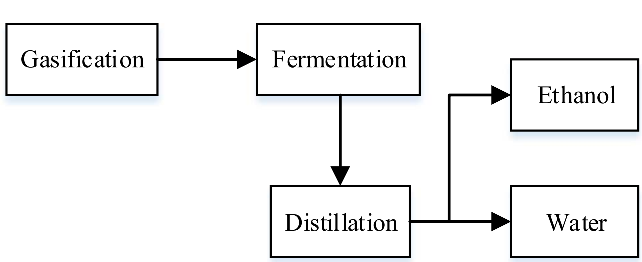

Fig. 21. Percentage yield of Ethanol, Glucose and Xylose with variations in solid and recycle ratio [113].

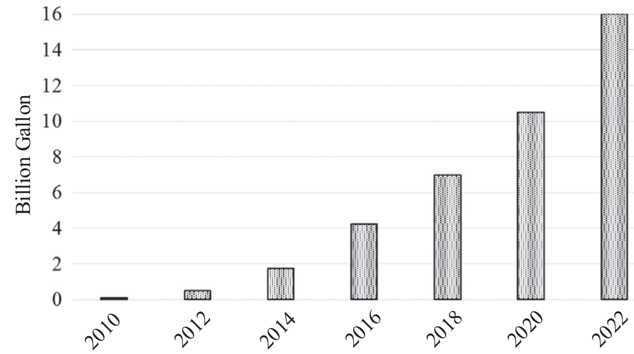

Fig. 22. The required aggressive increase in advanced biofuels as per energy independence and security act 2007 in USA [122].

estimated cost varies widely between investigations; [119,120] shows an estimated cost in the range of 0.28 to 1USD. Most of these cost estimates are based on the laboratory scale. Similarly, the capital cost also varies considerably between investigations. Various factors like raw material cost, the cost of hydrolysis, and initial processing cost contributes to the total cost of the process. Therefore, the cost of the process is highly influenced by the local conditions and prices [121].

In 2005, The renewable fuel standard was enacted as a part of energy policy and was amended in 2007 by the US congress. The aim was to encourage the use of biofuels. It was mentioned as a target that, by 2022 the volume of cellulosic biofuel should be raised to 16billion gallons. This will be in addition to the 15 billion gallons of conventional corn-based ethanol. An yearly progressive chart for achieving the task of 16 billion gallons by 2022 is shown in Fig. 22 [122].

3.4.3. Future prospects, challenges, and drawbacks

Biofuels in general, cellulosic ethanol and other advanced biofuels in special are currently supported at various levels by different states, countries, and local governments. These supports may be by mandating the use of biofuels, subsidizing and tax credits, funding for pre-commercial scale plants and much more.

There are various challenges to conquer for the researchers and industrialist in the field of cellulosic ethanol to make it available commercially. Major challenges are either in the formation of commercial level plants or are related to the technical aspects of the process [121]. Some of the major challenges are as follows:

- Improving the enzymatic hydrolysis. This includes the use of efficient enzymes, reduction in enzyme production cost and introduction of new and novel technologies for handling high solids.
- Development of more robust fermenting organisms. These microbes should be more tolerant to inhibitors, able to ferment all sugars in the raw material, ability to work in concentrated hydrolysis, and produce high ethanol concentration.
- Reduction in the number of steps in the cellulosic ethanol formation by extending the process integration. This can be done by reusing the process streams to eliminate the use of fresh water to decrease the amount of waste streams.

Despite the fact that cellulosic ethanol is a promising sustainable energy source and it possesses various advantages, there are some drawbacks also which are associated with this technology. The fuel is more corrosive and it tends to absorb water from the atmosphere. This may contaminate it as a fuel makes it difficult to ship through conventional pipes. In addition, cars would also need to be modified; it is incompatible with most of the components of existing car engines.

3.5. Artificial photosynthesis (AP)

Before going into detail on artificial photosynthesis, an under-

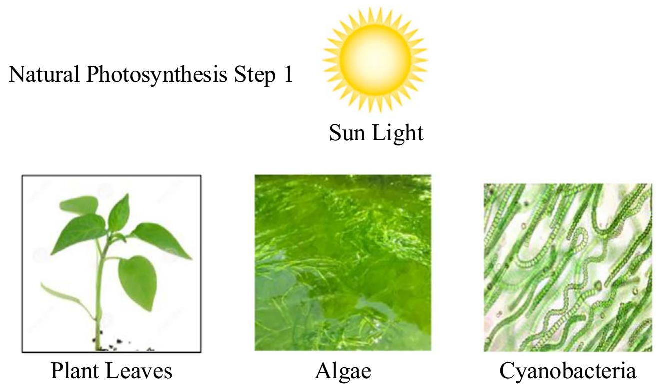

Fig. 23. Absorption of sun rays by a photoautotroph [124].

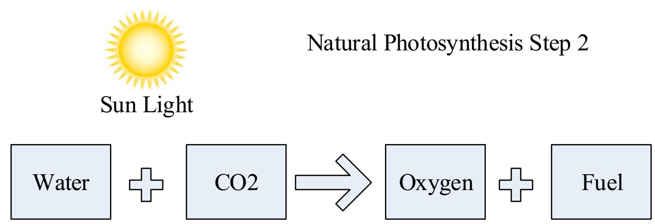

Fig. 24. Formation of fuel and oxygen from carbohydrates [124].

standing and functioning of the natural process of photosynthesis are necessary. In nature, photosynthesis plant's leaves, green algae and some other organism like cyanobacteria convert light energy into chemical energy that can be later released and used as an energy source by those organisms to fuel their activities. The converted chemical energy is stored in the form of carbohydrates such as sugars, which are synthesized from CO2 and water. During this process, oxygen gas is released as a byproduct. The natural process of photosynthesis is comprised of two major steps as shown in Fig. 23 and Fig. 24, respectively. Leaves of plants, algae and cyanobacteria absorb the light energy, mostly sunlight energy, from the sun.

After converting the sunlight energy by these photoautotrophs (organisms which absorb sunlight and make chemical energy), the stored chemical energy in the form of carbohydrates is utilized by these organisms to carry out their activities. The second step uses the water and CO_2, which are ingredients of the stored carbohydrates to generate fuel and oxygen gas. The produced fuel is used by these organisms, and oxygen is released into the air and is utilized by humans and other living creatures on the earth.

It can be observed in Step 2 of the natural photosynthesis that the process of photosynthesis not only generates fuel but it also releases oxygen as a byproduct. The benefits of mimicking the process of photosynthesis can benefit the living organism on earth twofold. The name, artificial photosynthesis, was given because of the desire to mimic to nature's unique arsenal of photosynthesis [123,124]. The aim is to store the energy from sunlight in high-energy chemical bonds [125,126]. Efforts have been made to decompose water into hydrogen and oxygen with acceptable conversion efficiencies [125]. The major benefit associated with this decomposition is that hydrogen is a good energy carrier and can be easily converted to electrical power. The process of generating power from hydrogen is environment-friendly, since it does not generate any byproduct harmful to the environment [127,128].

Artificial photosynthesis is the process of deriving energy from sunlight and water. There are three basic steps for photosynthetic water splitting. The first step is light harvesting the molecule chlorophyll (P). Second is tyrosine, which mediates the transportation of electrons and also acts as catalysis for the reaction. The final is the Manganese (Mn) complex, which is responsible for sending electrons to the chlorophyll.

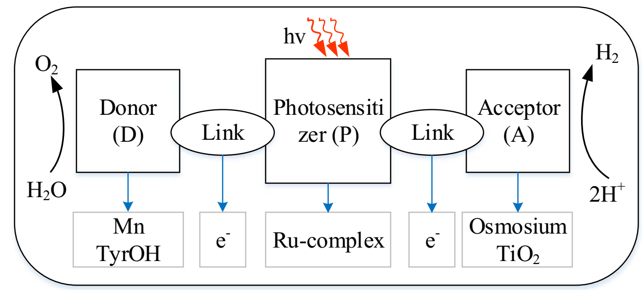

Fig. 25. Block diagram of Artificial Photosynthesis [129].

It forms an active surface for splitting the water [129,130]. A block diagram of the artificial photosynthesis process is shown in Fig. 25.

The main concept of solar based fuels is the transduction of sunlight energy to chemical bonds, which is also the case of artificial photosynthesis. In AP, this energy transduction can be achieved by making use of semiconductors, which have the ability to absorb sunlight and generate an electron-hole pair [131]. The energy of this electron-hole pair should be sufficient enough to carry out the electrochemical oxidation of water to convert it into oxygen and reduction of protons and CO_2 to convert them to chemical fuels. The energy required to split a water molecule into hydrogen and oxygen requires 1.23 V and reduction of CO_2 for the formation of methane requires 1.4–1.6 V [125]. The energy gap in semiconductors depends on the type of material used and is normally not within the above-stated ranges. Researchers have tackled this issue by employing two light absorbing components. Two materials with smaller band gap are used to absorb a greater portion of the solar spectrum. A sufficient photovoltage can be maintained by careful orientation of their conduction and valence band energy locations [130].

Sunlight is one of the major sources for generating renewable and sustainable energies, which are not harmful to the environment. There are various ways of harvesting and using solar energy for fulfilling the energy needs of the modern society [132]. Artificial photosynthesis is considered.

the direct way of converting sunlight into useful fuels and energy. Apart from this direct way, there are some semi-direct ways and indirect ways also. A summary of all these for converting solar energy into other useful forms of energy without harming the environment are shown in Fig. 26 [133].

3.5.1. Concept of artificial photosynthesis devices

The process of AP has the same principle of electron flow as that of natural photosynthesis. The reduction equivalents obtained by photosystem II (PSII) during water oxidation are transferred to the redox carriers through photosystem I (PSI), and then these are used to produce natural fuel nicotinamide adenine dinucleotide phosphate (NADPH). Several devices have been designed for carrying out the process of artificial photosynthesis [134]. Details of some the devices are given in the following sections:

3.5.1.1. Semiconductor particles. Semiconductors are able to excite electrons into higher energy gaps and to overcome the energy gap. Both single semiconductor particle and two semiconductor particle approaches are common for splitting water molecules [135]. The efficiency of 6.5% has been achieved through the two-step photoexcitation [136].

3.5.1.2. Electrolyzers. In Electrolyzers, water is split by using catalysts. These catalysts are deposited on the surface of the electrodes [137]. Commercially available electrolyzers have shown an efficiency of 8% [138]. The major drawback with this technology is all the metals used as an electrode are very expensive.

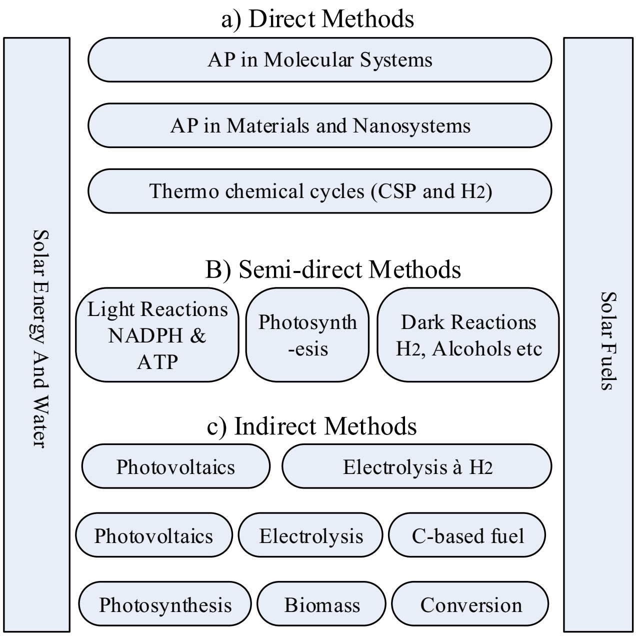

Fig. 26. Methods of converting solar energy into solar fuels [123].

3.5.1.3. Artificial leaf. The artificial leaf is a solar water-splitting cell. It includes earth-abundant elements, and these elements operate in near neutral PH conditions. They may or may not use the connecting wires [139]. An efficiency of 4.7% has been achieved with the wired configuration and 2.5% with the wireless configuration [139].

3.5.1.4. Dye-sensitized solar cells. Immobilization of molecular dyes at the surface of semiconductors can increase the efficiency of light harvesting. The dye-sensitized semiconductor particles are immobilized at a conducting surface in the dye-sensitized solar cells [140].

3.5.2. Future prospects, challenges, and drawbacks

Artificial photosynthesis is a promising source of energy for the future and has the ability to produce solar fuels efficiently. Currently, there is much room for improvement in all the basic four steps utilized for converting solar energy into electric power energy. The major bottlenecks in the process of AP are the catalytic steps, which are needed for oxidation of water and production of fuels. It is expected that within the next 10 years, small demonstration scale systems will be launched, based on the AP that can make solar fuels [141]. Research in the field of AP is at a fascinating stage.

The major source for driving AP is the advancements in the field of nanotechnology. Nanotechnology has been considering several areas of AP like light capturing, transportation of electrons, splitting of water and storage of hydrogen [142]. There is a race between different metals like haematite, cobalt, and manganese for an inexpensive electrode. There are still several safety concerns over the hydrogen storage and transportation due to the low energy density of hydrogen gas. Other research areas in this area are the production of methanol and how to make the AP system capable of using the hydrogen generated from water splitting and atmospheric CO_2 to store in the form of formic acid [143].

Until now, several laboratory prototypes of systems have been made that use sunlight to split water to produce hydrogen. The US announced an efficient prototype of artificial leaf in 2011. However, the long-term stability of the prototype has not been proven yet. Honda

Table 8
Summary of Emerging Renewable Energy Technologies.

Energy Type	Major Technologies	Energy Harvesting Method/Tool	Major Energy Source	Drawbacks	Ref.
Marine energy	Wave energy Tidal energy Tidal/Ocean currents Salinity gradient Ocean thermal energy conversion	Wave energy converters Tidal barrages Tidal current converters Pressure-retarded osmosis Open, close, and hybrid cycles	Wind Relative motion of earth, moon, and sun Rise and fall of tides Difference in salt concentration two liquids Solar energy	Influence on marine life Reduction of recreational areas Exposure to sea storms	[27] - [68] [144] [145]
Concentrated solar power	Parabolic trough Linear Fresnel reflectors Parabolic dishes Solar towers	Parabolic mirrors Long and slightly curved mirrors Dish shape mirror Heliostats	Solar irradiations	Requirement of large area Transmission/ distribution losses Very location specific	[60] [69] - [86] [146] [147]
Enhanced geothermal energy	–	Siting and developing of EGS reservoirs	Thermal energy stored in earth crust	May cause small earthquakes Minor environmental issues Location specific and equipment corrosion	[87] - [106] [148] [149]
Cellulosic ethanol	Celluloysis Gasification	Pre-treatment, hydrolysis and fermentation Fermentation and distillation	Inedible parts or remnants of plants	Difficulty in shipment Car engine upgradation Contamination of fuel	[107]- [123] [150] [151]
Artificial photosynthesis	Semiconductor particles Electrolyzers Artificial leaf Dye-sensitized solar cells	Two-step photo excitation Water splitting by using catalysts Water splitting by using earth abundant elements Immobilization of molecular dyes	Sunlight and water	Safety concerns over storage/ transportation Corrosion of equipment Sensitivity of catalyst to oxygen	[124]- [143] [152] [153]

(a car manufacturing company in Japan) announced the solar hydrogen station in the USA in 2010 [143]. It is still not clear that which process will emerge as the most commercially viable process in terms of efficiency, durability, and cost.

Similar to other emerging renewable energy sources, AP also has a huge potential and a lot of research is carried out on improving various aspects of this technology. However, there are some potential drawbacks of this technology also. There are safety concerns over the hydrogen storage and transportation due to the low energy density of hydrogen gas. Most of the hydrogen catalysts are sensitive to oxygen hence their performance is degraded or inactivated. Secondly, the materials used for AP often corrode in water and cause stability issues.

4. Conclusions

A comprehensive survey of emerging renewable technologies such as ocean energy, concentrated solar power, enhanced geothermal energy, cellulosic ethanol and artificial photosynthesis was made in this paper. This technology review has given an overview that currently, all the combined contribution of renewable energy sources is about 22% (June 2014). The rise in the level of greenhouse gasses has reached an alarming level. IEA has warned that the concentration of CO_2 will be doubled by 2050 under prevailing policies, as compared to the current amount in the atmosphere.

This review has also given an insight of the development and scope of CO_2 mitigation for renewable, clean and sustainable development. This paper has enlightened the researchers about the current status of the top five emerging renewable and sustainable energy sources. It also discusses the deadlocks and challenges faced by the researchers in each of the five mentioned technologies and suggests some of the potential solutions for the mentioned problems. The potential of each of the five emerging renewable technologies is enormous and has shown that each of these has the potential to suffice the energy needs of humans on earth in a sustainable way.

Inside each of the five main emerging technologies, there are still sub-technologies. With this broad variety of technologies, which make the emerging renewable energy, some of these technologies are already making their inroads in the marketplace and are at grid parity. While some of these technologies are further from commercialization, those are perhaps the most beneficial to the future's sustainable energy. Moreover, the progress rate of all of these technologies is faster than ever. There are some technical obstacles for some of the emerging technologies, but the progress of research shows that these hurdles will be overcome soon. The mainstream renewable energy sources along with the emerging renewables have the potential to replace the conventional environmentally hazardous energy technologies, and these renewables will soon completely replace them. The concept of smart cities has given a boost to these renewables, and these are the main source of clean and environment-friendly energy sources of near future.

The need of the hour is to support these renewable technologies and especially emerging renewable technologies to make the earth a clean and hazard-free place for living beings. The support could be by creating awareness, helping in overcoming the technological barriers, subsidized and tax-free policies by local governments and by mandating the use of environment-friendly energy sources.

All the five emerging renewable energy sources are summarized in Table 8. Energy harvesting methods, major energy sources, and drawbacks are also presented.

References

[1] Flavin C, O Meara M. Financing solar electricity. World Watch 1997;10(3):261–74.
[2] Ricardo Guerrero-Lemus, Jose´ Manuel Martınez-Duart. Renewable Energies and CO_2 (2012 Edition). pp 9-31
[3] The clouds of unknowing.The Economist; 2010.
[4] Pan Y. A large and persistent carbon sink in the world's forests. Science 2011;333:988–93.
[5] Earth System Research Laboratory. Global Monitoring Division. National Oceanic and Atmospheric Administration. U.S. Department of Commerce; 2005.
[6] Demirbas A. Recent advances in biomass conversion technologies. Energy Educ Sci Technol 2000;6:19–40.
[7] Rathore NS, Panwar NL. Renewable energy sources for sustainable development. New Delhi, India: New India Publishing Agency; 1996.
[8] Panwara NL, Kaushik SC, Kothari Surendra. Role of renewable energy sources in environmental protection: a review. Renew Sustain Energy Rev 2011;15:1513–24.
[9] Reddy AKN, Subramanian DK. The design of rural energy centers, 2. Bangalore: Indian Academy of Science; 1980. p. 109–30.
[10] Ravindranath NH, Hall DO. Biomass, energy, and environment: a developing country perspective from India. Oxford, United Kingdom: Oxford University Press; 1995.
[11] REN21. Renewable energy PolicyNetworkfor the 21st century. Renewables 2014. Global Status Report; 2016.
[12] UNDP. World energy assessment 2000—energy and the challenge of sustainability.New York: UNDP; 2000 (ISBN 9211261260).
[13] FS-UNEP Collaboration Center, Frankfurt School. Global trends in renewable energy investments; 2016.
[14] EIA Annual Report 2014. USEnergy information Administration (EIA); 2014.
[15] IRENA, roadmap for a renewable energy future; 2016edition.
[16] Dincer I. Renewable energy and sustainable development: a crucial review. Renew Sustain Energy Rev 2000;4(2):157–75.
[17] Sharma A, Chen CR, Lan NV. Solar-energy drying systems: a review. Renew Sustain Energy Rev 2008;13(6–7):1185–210.
[18] Okoro OI, Madueme TC. Solar energy: a necessary investment in a developing economy. Int J Sustain Energy 2006;25(1):23–31.
[19] Kumar A, Kandpal TC. Potential and cost of CO_2 emissions mitigation by using solar photovoltaic pumps in India. Int J Sustain Energy 2007;26(3):159–66.
[20] Kralova I, Sjoblom J. Biofuels-renewable energy sources: a review. J Dispers Sci Technol 2010;31(3):409–25.
[21] lorenteI L, lvarez JL A´, Blanco D. Performance model for parabolic trough solar thermal power with thermal storage: comparison to operating plant data. Sol Energy 2011;85:2443–60.
[22] Gaudiosi G. Offshore wind energy prospects. Renew Energy 1999;16(1–4):828–34.
[23] Barbier E. Geothermal energy technology and current status: an overview. Renew Sustain Energy Rev 2002;6:3–65.
[24] Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, et al. The path forward for biofuels and biomaterials. Science 2006;311(5760):484–9.
[25] Wydrzynski TJ, Satoh K. (editors). Photosystem II: The Light-DrivenWater: PlastoquinoneOxidoreductase, Advances in Photosynthesis and Respiration; 2006; 87. p. 331–5.
[26] International Energy Agency. Renewables in global energy supply. An IEA facts sheet OCED; 2007.
[27] J. Crus Ed. Ocean Wave Energy: Current Status and Future Perspectives. Springer: Berlin; 2008
[28] Vining JG, Muetze A. Economic factors and incentives for ocean wave energy conversion. IEEE Trans Ind Appl 2009;45(2):547–54.
[29] Takahashi P, Trenka A. Ocean thermal energy conversion. New York: Wiley; 1996.
[30] Pelc Robin, Fujita Rod M. Renewable energy from the ocean. Mar Policy 2002;26:471–9.
[31] Gareth P, Harrison , Robin Wallace A. Climate sensitivity of marine energy. Renew Energy 2005;30:1801–17.
[32] Shields a Mark A, Woolf DK. The ecological implications of altering the hydrodynamics of the marine environment Ocean & coastal management. Mar Renew Energy 2011;54:2–9.
[33] Boehlert Gorge W, Gi l l An drew B. Environmental and ecological effects of ocean renewable energy development. Oceanography 2010;23(2):68–81.
[34] Wright Glen. Marine governance in an industrialized ocean: a case study of the emerging marine renewable energy industry. Mar Policy 2015;52:77–84.
[35] Kerr Sandy, Colton John, Johnson Kate, Wright Glen. Rights and ownership in sea country: implications of marine renewable energy for indigenous and local communities. Mar Policy 2015;52:108–15.
[36] Quirapas Ann Joy Robles, Lin Htet. Ocean renewable energy in Southeast Asia: a review. Renew Sustain Energy Rev 2015;41:799–817.
[37] Lewis A, Estefen S, Huckerby J, Musial W, Pontes T, Torres-Martinez J. Ocean energy. IPCC Spec Rep Renew Sources Clim Change Mitig 2011, [chapter 6].
[38] OES, Annual report on implementing agreement on ocean energy systems; 2014
[39] Clement Alain, Cullen Pat Mc. Wave energy in Europe: current status and perspectives. Renew Sustain Energy Rev 2002;6:405–31.
[40] Titah-Benbouzid Hosna, Benbouzid Mohamed. IEEE Electronics and Application Conference and Exposition (PEAC), France:338–342; 2014.
[41] Falcao FAO. Wave energy utilization: a review of the technologies. Renew Sustain Energy Rev 2010;14(3):899–918.
[42] Muller N, Kouro S, Glaria J, Malinowski M. Medium-voltage power converter interface for Wave Dragon wave energy conversion system. In: Proceedings of the IEEE ECCE, Denver (USA): 352–358; 2013.
[43] Muller MA. Electrical generators for direct drive wave energy converters. IEE Proc Gener Transm Distrib 2002;149(4):446–56.
[44] Berrie, T.W. The Economics of System Planning in Bulk Electricity Supply. Electrical Review, A series of three articles: 15. 22. 29 of September 1967
[45] Olaya S, Bourgeot JM, Benbouzid MEH. Modelling and preliminary studies for a

self-reacting point absorber WEC. inProceedings of the IEEE ICGE, Sfax (Tunisia):14-19; 2014.
[46] The Energy Daily. SMUD Will Cancel Solar Plant if Bids Don't Drop; 1985. 13(40): 1–6
[47] Lagoun MS, Benalia A, Benbouzid MEH. A predictive power control of doubly fed induction generator for wave energy Converter in irregular waves. In: Proceedings of the IEEE ICGE, Sfax (Tunisia); 2014: 26–31
[48] Lagoun MS, Nadjem S, Benalia A, Benbouzid MEH. Predictive power control of doubly-fed induction generator for wave energy converters. In: Proceedings of the EFEA (International Symposium on Environment Friendly Energies and Applications), Newcastle upon Tyne (UK):312–317; 2012.
[49] Alberdi M, Amundarain M, Garrido AJ, Garrido I. Neural control for voltage dips ride-through of oscillating water column-based wave energy converter equipped with doubly-fed induction generator. Renew Energy 2012;48:16–26.
[50] Alberdi M, Amundarain M, Garrido AJ, Garrido I, Maseda FJ. Fault-ride-through capability of oscillating-water-column-based wave power- generation plants equipped with doubly fed induction generator and airflow control. IEEE Trans Ind Electron 2011;58(5):1501–17.
[51] International Renewable Energy Agency, Ocean Energy Technology readiness, patents, Deployment status and outlook, Report; 2014.
[52] Bryden Ian G, Scott , Couch J. ME1—marine energy extraction: tidal resource analysis. Renew Energy 2006;31:133–9.
[53] Leaman KD, Molinari RL, Vertes PS. Structure and variability of the Florida current at 27A°N. J Phys Oceanogr 1978;17(5):565–83.
[54] Hammons TJ. Tidal power modeling the operation and maintenance costs of a large scale tidal current turbine farm. Proc IEEE 1993;89(3):419–33.
[55] Woolf DK, Cotton PD, Challenor PG. Measurements of the offshore wave climate around the British Isles by satellite altimeter. Philos Trans: Math Phys Eng Sci 2003;361:27–31.
[56] Bahaj AS, Myers LE. Fundamentals applicable to the utilization of marine current turbines for energy production. Renew Energy 2003;28:2205–11.
[57] Fraenkel PL, Clutterbuck P, Stjernstrom B, Bard J. Proc 3rd European Wave Energy Conference Incorporating Waves, Tidal and Marine Currents; 1998
[58] Fraenkel PL. Tidal currents A major new source of energy for the Millenium EEZ Technology, 4th ed.. London: ICG Publishing Ltd; 1999.
[59] Bryden IG, Naik S, Fraenkel P, Bullen CR. Matching tidal current plants to local flow conditions. Energy 1998;23(9), [699-09].
[60] Scramesto OS, Skilhagen S-E, Nielsen WK. Power production based on osmotic pressure.In: Waterpower XVI, Spokane, WA, USA; 2009.
[61] Van den E nde, K., F. Groeman.Blue Energy. Leonardo Energy, KEMA Consulting, Arnhem, The Netherlands; 2007
[62] Loeb S, Norman RS. Osmotic power plants. Science 1975;189(4203):654–5.
[63] International Renewable Energy Agency, Salinity Gradient Energy, Technology brief, Report; 2014.
[64] Stenzel P. Potentials of the osmosis for generating and storing of electricity. Energy Sustain 2012;4(978):643–50.
[65] Kim NJ, Ng KC, Chun W. Using the condenser effluent from a nuclear power plant for Ocean Thermal Energy Conversion [OTEC]. Int Commun Heat Mass Transf 2009;36:1008–13.
[66] Yuan Han, Mei Ning, Zhou Peilin. Performance analysis of an absorption power cycle for ocean thermal energy conversion. Energy Convers Manag 2014;87:199–207.
[67] International Renewable Energy Agency, Ocean Thermal Energy Conversion, Technical brief; 2014.
[68] US Department of Energy. International energy outlook 2002 Report #: DOE/EIA-0484(2002); 2002
[69] Muller-Steinhagen H, Trieb F. Concentrating solar power: a review of the technology. Ingenia 2014;18:43–50.
[70] Greenpeace, Solar thermal electricity global outlook; 2016.
[71] IEA-ETSAP and IRENA, technology brief, concentrating solar power; 2013
[72] IRENA, Renewable energy technologies: cost analysis series, concentrating solar powe; 2012.
[73] Barlev David, Vidu Ruxandra, Stroeve Pieter. Innovation in concentrated solar power: review. Sol Energy Mater Sol Cells 2011;95:2703–25.
[74] Zhang HL, Baeyens J, Degreve J, Caceres G. Concentrated solar power plants: review and design methodology. Renew Sustain Energy Rev 2013;22:466–81.
[75] lorenteI L, lvarez A, Blanco D JL. Performance model for parabolic trough solar thermal power with thermal storage: comparison to operating plant data. Sol Energy 2011;85:2443–60.
[76] Barlev D, Vidu R, Stroeve P. Innovation in concentrated solar power. Sol Energy Mater Sol Cells 2011;95(10):2703–25.
[77] Fernandes D, Pitie F, Caceres G, Baeyens J. Thermal energy storage how previous findings determine current research priorities. Energy 2012;39(1):246–57.
[78] Mousazadeh H. A review of principle and sun-tracking methods for maximizing solar systems output. Renew Sustain Energy Rev 2009;13(8):1800–18.
[79] Liu QB. Experimental investigation on a parabolic trough solar collector for thermal power generation. Sci China-Technol Sci 2010;53(1):52–6.
[80] Paxson. Design and Validation of an Air Window for a Molten Salt Solar Thermal Receiver. SB Thesis MIT; 2009.
[81] Cole IR, Betts TR, Gottschlag R. Solar profiles and spectral modeling for CPV simulations. IEEE J Photovolt 2012;2(1):62–7.
[82] Madaeni SH, Sioshansi R, Denholm P. Estimating the capacity value of concentrating solar power plants: a case study of the southwestern United States. IEEE Trans Power Syst 2012;27(2):1116–24.
[83] Sioshansi R, Denholm P. The value of concentrating solar power and thermal energy storage. IEEE Trans Sustain Energy 2010;1(3):173–83.
[84] US Department of energy, 2014: The year of concentrated solar power; 2014
[85] RENAC Renewables Academy.ReGrid: Concentrated Solar Power; 2012
[86] Barlev D, Vidu R, Stroeve P. Innovation in concentrated solar power. Sol Energy Mater Sol Cells 2011;95(10):2703–25.
[87] John ziagos, benjamin r. Phillips, laurenboyd, allanjelacic, gregstillman, and erichass. A technology roadmap for strategic development of enhanced geothermal systems. In: Proceedings of the thirty-eighth workshop on geothermal reservoir engineering Stanford university, stanford, California. 2013
[88] Kewen Li, Huiyuan Bian, Changwei Liu, Danfeng Zhang, Yanan Yang. Comparison of geothermal with solar and wind power generation systems. Renew Sustain Energy Rev 2015;42:1464–74.
[89] David K Garman, US department of energy.geothermal technologies program: Enhanced geothermal systems; 2004
[90] Md. Riyasat Azim, Md. Shahedul Amin, Md. AsaduzzamanShoeb. Prospect of Enhanced Geothermal System in Baseload Power Generation. IEEE International Conference on Advanced Management Science (ICAMS); 2010. pp.176–80.
[91] MIT, the future of Geothermal Energy impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st century; 2006.
[92] Blackwell David D, Negraru Petru T, Richards Maria C. Assessment of the enhanced geothermal system resource base of the United States. Nat Resour Res 2006;15(4):283–308.
[93] US department of energy.An evaluation of enhanced geothermal systems technology: Geothermal technologies program; 2008
[94] Polizzotti, RS, LL Hirsch, AB Herhold, MD Ertas.Hydrothermal Drilling Method and System. Patent publication date; 2003
[95] Nalla G, Shook GM. Engineered geothermal systems using advanced well technology. Geotherm Resour Counc Trans 2004;28:117–23.
[96] Sanyal SK, Butler SJ. An analysis of power generation prospects from enhanced geothermal systems. Geotherm Resour Counc Trans 2005;29:1–6.
[97] Vuatarez F-D. Review of the Papers on HDR and Enhanced Geothermal Systems. In: Proceedings of the World Geothermal Congress. Kyushu-Tohoku, Japan; 2000.
[98] Brown D. A hot dry rock geothermal energy concept utilizing supercritical CO2 instead of water. In: Proceedings of the twenty-fifth workshop on geothermal reservoir engineering, Stanford University: 233–238; 2000.
[99] Aljundi IH. Effect of dry hydrocarbons and critical point temperature on the efficiencies of organic Rankine cycle. Renew Energy 2011;36(4):1196–202.
[100] Coleman JL, Cahan SM. Preliminary catalog of the sedimentary basins of the United States. US Geol Surv Open-file Report 2012:1102–11.
[101] Xu C, Dowd PA, Mohais R. Connectivity analysis of the Habanero enhanced geothermal system. In: Proceedings of the 37th workshop on geothermal reservoir engineering, Stanford; 2012.
[102] Zimmermann G, Blocher G, Reinicke A, Brandt W. Rock specific hydraulic fracturing and matrix acidizing to enhance a geothermal system: concepts and field results. Tectono Phys 2011;503:146–54.
[103] Lacirignola M, Blanc I. Environmental analysis of practical design options for enhanced geothermal systems (EGS) through life-cycle assessment. Renew Energy 2013;50:901–14.
[104] Pruess Karsten. On production behavior of enhanced geothermal systems with CO_2 as working fluid. Energy Convers Manag 2008;49:1446–54.
[105] Mohan Arun Ram, Turag Uday, Subbaraman Viswanathan, Shembekar Vishakha, Elsworth Derek, Sarma , Pisupatia V. Modeling the CO_2-based enhanced geothermal system (EGS) paired with integrated gasification combined cycle (IGCC) for symbiotic integration of carbon dioxide sequestration with geothermal heat utilization. Int J Greenh Gas Control 2015;32:197–212.
[106] Randolph Jimmy B, Saar Martin O. Combining geothermal energy capture with geologic carbon dioxide sequestration. Geophys Res Lett 2011;38:LI0401.
[107] Granda , Cesar B, Zhu L, Holtzapple MT. Sustainable liquid biofuels and their environmental impact. Environ Progress 2007;26(3):233–50.
[108] Farrell AE, Plevin RJ. Ethanol can contribute to energy and environmental goals. Science 2006;311(5760):506–8.
[109] IEA, Biofuels for transport: an international perspective. Interview by International Energy Agency; 2006
[110] Mabee WE, Gregg DJ, Sadler JN. Ethanol from Lignocellulosics: Views to implementation. IEA Task 39 ReportT39-P1; 2004.
[111] U.S. Department of Energy Biomass Program.Theoretical ethanol yield calculator and biomass feedstock composition and property database; 2013
[112] Nwakaire JN, Ezeoha SL, Ugwuishiwu BO. Production of cellulosic ethanol from wood sawdust. Agric Eng Int: CIGR J 2013;15(3):136–40.
[113] NERL USA. Innovation for our energy future: Cellulosic ethanol; 2007.
[114] Rajagopalan Srini, Datar Rohit P, Lewis Randy S. Formation of ethanol from carbon monoxide via a new microbial catalyst. Biomass Bioenergy 2002;23(6):487–93.
[115] Hunt DV. The gasohol handbook. New York, NY: Industrial Press; 1981. p. page580.
[116] Henry Ford Kovarik B. Charles Kettering and the “fuel of the future”. Automot Hist Rev 1998;32:7–27.
[117] Sievers D, Tao L, Schell DJ. Performance and techno-economic assessment of several solid-liquid separation technologies for processing dilute-acid pretreated corn stover. Bioresour Technol 2014;167:291–6.
[118] Katatzos, S, McMillan JD, Saddler JN. The potential and challenges of drop-in biofuels. A Report by IEA Bioenergy Task 39, Report T39-T1; 2014
[119] Von Sivers M, Zacchi G. Ethanol from lignocellulosics: a review of the economy. Bioresour Technol 1996;56:131–40.
[120] Lynd L. Likely features and costs of mature biomass ethanol technology. Appl Biochem Biotechnol 1996;57:741–60.
[121] Hahn-Ha¨ gerdal B, Galbe M, Gorwa-Grauslund MF, Lide´n G, Zacchi G. Bio-

ethanol – the fuel of tomorrow from the residues of today. Trends Biotechnol 2006;24(12):549–56.
[122] Kim Tae Hoon, Kim Tae Hyun. Overview of technical barriers and implementation of cellulosic ethanol in the U.S. Energy 2014;66:13–9.
[123] Huib de Vriend, Robin Purchase. Solar Fuels and Artificial Photosynthesis.Science and innovation to change our future energy option; 2013
[124] American Society for Microbiology. Bacteria Use Hydrogen, Carbon Dioxide to Produce Electricity. Press Release; 2013
[125] Liu Chong, Dasgupta Neil P, Yang Peidong. Semiconductor nanowires for artificial photosynthesis. Chem Mater 2013;25:415–22.
[126] Fujishima A, Honda K. Nature 1972;238:37–8.
[127] Crabtree GW, Dresselhaus MS, Buchanan MV. The hydrogen economy. Phys Today 2004;57(2):39–44.
[128] Kim Dohyung, Sakimoto Kelsey K, Hong Dachao, Yang Peidong. Artificial photosynthesis for sustainable fuel and chemical production. Chem Int 2015;54:3259–66.
[129] Huijie Qi. Photosynthesis and artificial photosynthesis. Hong Kong: Institute of Precision Engineering. The Chinese University of Hong Kong; 2007, ⟨http://www.ipe.cuhk.edu.hk/⟩.
[130] Shin Sun-Mi, Jung Jin-Young, Park Min-Joon, Song Jae-Won, Lee Jung-Ho. Catalyst-free hydrogen evolution of Si photocathode by thermovoltage-driven solar water splitting. J Power Sources 2015;279:151–6.
[131] Lee MH, Takei K, Zhang J, Kapadia R, Zheng M, Chen Y-Z, Nah J, Matthews TS, Chueh Y-L, Ager JW, Javey A. Angew. p-type inp nanopillar photocathodes for efficient solar-driven hydrogen production. Chem Int 2012;51:10760–4.
[132] Barber J. Photosynthetic energy conversion: natural and artificial. Chem Soc Rev 2009;38:185–96.
[133] Uppsala university. Artificial photosynthesis for solar fuels(presentation); 2013
[134] Sergey Koroidov, [Ph.D. thesis]. Water splitting in natural and artificial photosynthetic systems, Department of Chemistry, Umeå, Sweden; 2014.
[135] Kudo . Z-scheme photocatalyst systems for water splitting under visible light irradiation. MRS Bull 2011;36:32–8.
[136] Maeda K, Domen K. Photocatalytic water splitting: recent progress and future challenges. J Phys Chem Lett 2010;1:2655–61.
[137] Lassali TAF, De Castro SC, Boodts JFC. Structural, morphological and surface properties as a function of composition of Ru+Ti+Pt mixed-oxide electrodes. Electrochim Acta 1998;43:2515–25.
[138] Armaroli N, Balzani V. Front Matter. In Energy for a sustainable world.Wiley-VCH Verlag GmbH & Co. KGaA; 2010: I–21.
[139] Esswein AJ, Surendranath Y, Reece SY, Nocera DG. Highly active cobalt phosphate and borate based oxygen evolving catalysts operating in neutral and natural waters. Energy Environ Sci 2011;4:499–504.
[140] Lee S-HA, Zhao Y, Hernandez-Pagan EA, Blasdel L, Youngblood WJ, Mallouk TE. Electron transfer kinetics in water splitting dye-sensitized solar cells based on core-shell oxide electrodes. Faraday Discuss 2013;155:165–76.
[141] Cogdel Richard J, Brotosudarmo Tatas HP, Gardiner Alastair T, Sanchez Pedro M, Cronin Leroy. Artificial photosynthesis-solar fuels: current status and future prospects. Biofuels 2010;1(6):861–76.
[142] Nam YS. Virus-templated assembly of prphyrins into light harvesting nanoantenne. J Am Chem Soc 2010;135(5):1462–3.
[143] Hull JF. Reversible hydrogen storage using CO_2 and a proton switch-able iridium catalyst in aqueous media under mild temp and pressure. Nat Chem 2012;4(5):383–8.
[144] Renewable green energy power, ⟨http://www⟩. renewable greenenergypower.com/wave-energy-pros-and-cons/
[145] Greentumble, ⟨http://greentumble.com/advantages-and-disadvantages-of-wave-power/⟩
[146] GENI, Review and comparison of different solar energy technologies; 2011
[147] Solar thermal: pros and cons – Part 2: Concentrating solar power, ⟨http://www.triplepundit.com/special/⟩ energy-options-pros-and-cons/solar-thermal-pros-cons-part-2-concentrating-solar-power/#
[148] Energy informative, Geothermal Energy Pros and Cons ⟨http://energyinformative.org/geothermal-energy-pros-and-cons/⟩
[149] IEEE spectrum, Geothermal energy's promise and problems, ⟨http://spectrum.ieee.org/green-tech/⟩geothermal-and-tidal/geothermal-energys-promise-and-problems
[150] Cellulosic ethanol: Pros & cons, ⟨http://greenthe⟩future.com/CELLETHANOL_PROSCONS.html
[151] The Disadvantages of cellulose biofuel, [Available online]⟨http://classroom.synonym.com/disadvantages-cellulose-biofuel-21790.html⟩
[152] Artificial photosynthesis - Advantages, disadvantages, and efficiency, ⟨http://www.liquisearch.com/artificial_⟩photosynthesis/advantages_disadvantages_and_efficiency
[153] Artificial photosynthesis pros and cons, ⟨http://www.ehow.com/info_8746742_artificial-hotosynthesis-pros-cons.html⟩