IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Sustainability indicators, economic and environmental impact of renewable energy resources

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ABSTRACT: *clean energy resources is going to be the most favourable and important resources form now onwards for electricity generation. Renewable electricity generation technologies were assessed against a range of sustainability indicators, the indicators used to asses were the greenhouse gas emission, cost of electricity, energy payback time, and availability of renewable resources, land requirement, energy conversion efficiency, water consumption and social impact. The cost of electricity, greenhouse gas emissions and the energy payback time were initiate to have a very extensive variety for each technology, which the figure of merit for different renewable energy sources has been proposed.*

The study indicates that wind energy is having minimum water consumption, minimum greenhouse gas emission, and most friendly social impacts which is considered as one of the most sustainable energy resources, small hydroelectric power plant stand in second followed by solar photovoltaic cell and geothermal as this resources is clean and most sustainable in nature, which can be helpful for mitigation of greenhouse gas emission, global warming.

1. Introduction:

Contributions and increasing the dependency on renewable energy sources, solar, wind, geothermal, combustible renewable energy sources and waste are used in all over the world in last two decade, due to its low emission, pollution, and named as the clean energy resources however the fossil fuel base type plant are going to in lower interest of market, For investigation and installation of renewable energy based system we also need to consider the sustainability measures because due to some of the stage in renewable there also effect on environment as we said the renewable is clean but during installation, transportation and some other activities, which the greenhouse gas emission, cost of the electricity and the energy payback time are to be calculated [1]

Statistics and estimated share of renewable energy in has been 26.2% which 15.8 hydro power, 5.5 wind, 2.4% solar, 2.2% bio power and 0.4% geothermal, CSP, and ocean energy [2] [3]

In 2020 the share of renewable has increased up to 28% which show the 1.2% growth in renewable but was expected to be more increase in share percentage of renewable, due to COVID-19 pandemic every activities has effected, renewable can meet 50% of total world energy in mid-21st century with new improvements in technology and system [4].

Coal fired and inflammable plant are having maximum CO2 par KWh of electricity and other pollutants are high as well but still huge generation plant are running around the world and more compatible in energy market due to its low cost per unit, and developing country is more dependent on the conventional type of electricity generation system. Mostly those activities which are responsible for greenhouse gas emission are transportation, electricity generation, manufacturing industries, constructions and demolitions.

Energy is the requirement for sustainable and renewable development of the recent civilization. Global energy need is expected to raise by 36% for the year 2011-30 with a share of 88% from the non-renewable (oil, natural gas, and coal) energy sources [8]. According to 2014 data, in the United States, the electricity sector and the transportation sector consumed 39% and 27% of the total energy, respectively, and most of the energy comes from petroleum with a share of 35% and natural gas with a share of 28%, respectively [9]. The electricity sector was the major greenhouse gas (GHG) emitting sector followed by the petroleum and natural gas sector, and the petroleum refinery sector, respectively [10]. In 2014, world's electricity production was 22,433 terawatt hours (TWh) and the shares of coal, natural gas, hydroelectric, nuclear, and liquid fuel were 39%, 22%, 17%, 11%, and 5%, respectively. Fossil fuel based [11]. Energy sources are depleting, and combustion of fossil fuels releases harmful GHGs into the atmosphere resulting in global warming and ozone layer depletion. Global CO2 emission was increased by 78% from the year 1981e2011 and will increase by 85% from year 2000e30 [12]. Different policy regulations have come into play to reduce GHG emissions by encouraging the use of more and more alternative sources, such as renewable energy sources. Renewable energy sources solar, wind and hydro power, geothermal, biomass, and so on dare now considered as sustainable alternatives. In 2014, renewable sources accounted for about 24% of the world's total energy generation [13], and by the year 2070, the share will be increased to 60%. [14]

The studies has been indicates the impact of energy generation on environment and economy are countable to take measure and evaluate, researchers and authors have conducted and analyse the life cycle statistics of individuals energy generation technology, and found the nuclear and photovoltaic cell are known as carbon emission free which during whole life cycle operation does not emit carbon emission, however there is some during the installation and system manufacturing which need to count and this similar for other renewable base generation system which this is too much high for conventional type generation, switching to renewable energy technologies provides merit on management guideline as well on economic and environment so for every energy sector should be recommended.

2. Sustainability indicators of renewable energy technologies

2.1 Energy payback time

Energy pay-back time (EPBT) means years to recover initial energy consumption through its life-cycle by its own energy production during the life-cycle. The total energy requirement for the electricity generation system and the yearly power generated are concerned with the initial energy. To exchange the annual power generation of system (kWhe) to primary energy, there is a requirement for the average efficiency of the electricity production projects. Estimation of energy pay-back time is shown by Eq 1

As a sample we can deliberate the energy payback time for solar photovoltaic PV system due to fast improving growth production technologies the energy pay-back time has been declining continuously since the introduction of photovoltaic systems in the energy sector. In 2000 the energy pay-back time of photovoltaic systems was estimated as 8-11 years and the year 2006 this was estimated to be 1.5 to 3.5 years for crystalline silicon solar cell systems and 1–1.5 years for thin film.These figures fell to 0.75–3.5 years in 2013, with an average of about 2 years for crystalline silicon PV and CIS systems

$$\mathrm{EPBT(years)} = \frac{\begin{array}{c}\text{Total primary energy requirement of system}\\ \text{throughout its life cycle(GJ)}\end{array}}{\begin{array}{c}\text{Annual primary energy generation by the system}\\ \left(\frac{\mathrm{GJ}}{\mathrm{year}}\right)\mu\end{array}} \ldots (1)$$

2.2 Greenhouse gas emission

Greenhouse gas emissions (gCO2eq/kWhe) were generally estimated according to the full operational life cycle of each renewable energy sources from the manufacturing of the plant to full operation of the system (birth to grave). These emissions are found to vary widely within each technology. For PV and wind energy system most of the emissions are the electricity usage during manufacturing. In these cases, an average grid mix for the region of manufacturing is typically used to calculate emissions. Estimation of greenhouse gas emissions is shown by Eq. (2).

$$\text{GHG emissions} = \frac{\begin{array}{c}\text{Total CO2 emissions throughout its} \\ \text{life cycle(gCO2)}\end{array}}{\text{Annaul power generation } \left(\frac{\text{KWh}}{\text{year}}\right) * \text{life time(year)}}$$

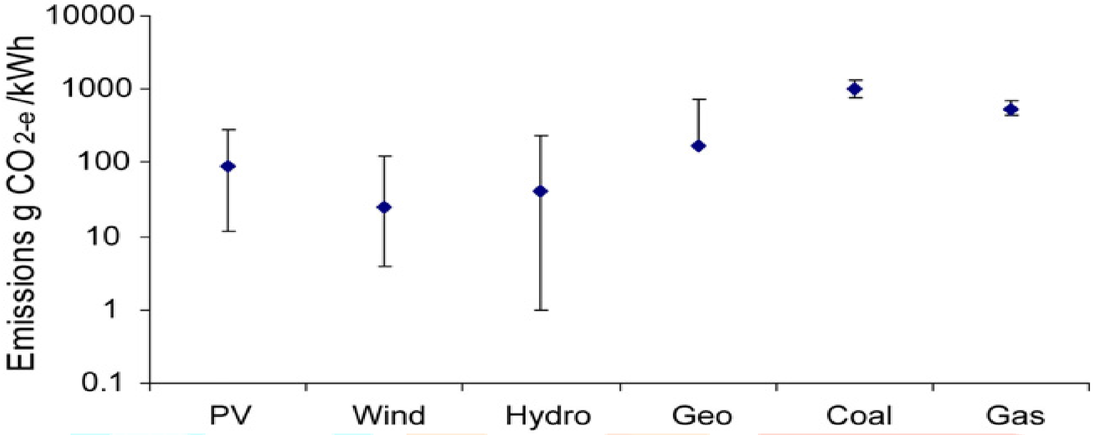
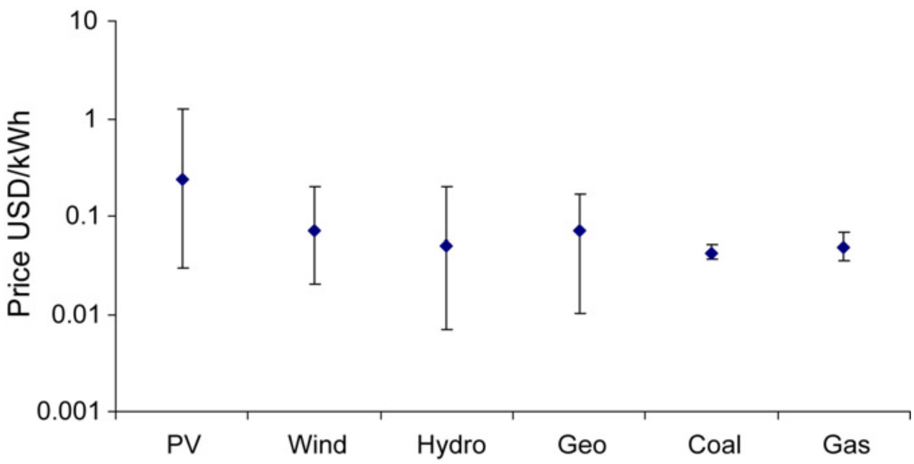


Fig. 2. Carbon dioxide equivalent emissions during electricity generation.

2.3 Cost of electricity generation

An average cost of production of electricity over the full life cycle of each generation technology accounting for construction, installation, operation, maintenance, decommissioning, recycling/ disposal. Intermittent renewable sources, i.e. PV and wind may require back up but these have not been included in cost calculations. Wide ranging values for the cost are seen for all the systems. Among all renewable sources, PV system has the widest range of cost for electricity generation due to various type of solar cells, and location specific variations, i.e. solar radiation intensity and electricity cost to manufacture cells. The cost of electricity generation has been reported in cents/kWhe prevalent in US and/or European Union. For purpose of calculations, the US currency has been taken equivalent to euro, as the two currencies have nearly the same value and the level of development in US and European Union is comparable. Estimation of cost of electricity generation is shown by Eq. (3).

Solar and wind power costs have continued to fall, complementing the more mature bioenergy, geothermal and hydropower technologies. Solar photovoltaic (PV) shows the sharpest cost decline over 2010-2019 at 82%, followed by concentrating solar power (CSP) at 47%, onshore wind at 40% and offshore wind at 29%.



Electricity costs from utility-scale solar PV fell 13% year-on-year, reaching nearly seven cents (USD 0.068) per kilowatt-hour (kWh) in 2019. Onshore and offshore wind both fell about 9% year-on-year, reaching USD 0.053/kWh and USD 0.115/kWh, respectively, for newly commissioned projects. Costs for CSP, still the least-developed among solar and wind technologies, fell 1% to USD 0.182/kWh

$$\text{Cost of electricity generation} = \frac{\text{Annaulised expenses of the system}\left(\frac{\text{cent}}{\text{year}}\right)}{\text{Anual electricty generation by the system}(\text{KWh? year})}$$

3. Renewable and sustainable energy resources

Unlike conventional power plants, whose electricity generation costs have become dominated by fuel costs (with the exception of nuclear power), the key aspects determining the costs of renewable systems are their investment cost and natural resource availability – such as solar irradiation, the wind resource or the availability of organic matter for biomass systems. The future cost trajectory of electricity generated from renewable sources depends in each case on a technology’s present maturity, its further development and economies of scale arising from the broad dissemination of corresponding systems. The explicit and implicit promotion of conventional systems is one of the greatest obstacles facing the expansion of renewable technologies, which some claim to be uneconomic.

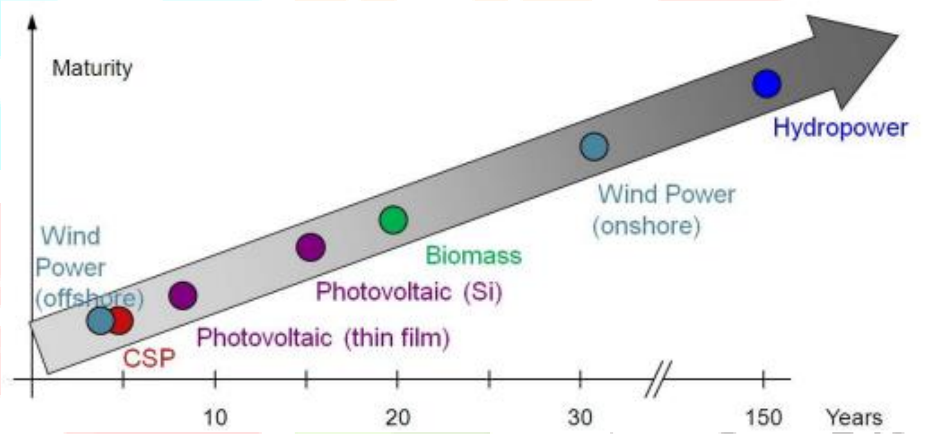


Figure 2: Technical maturity and duration of utilization of renewable energy technologies for the power generation

The International Energy Agency estimates that USD 312 billion in support for conventional energy technologies was provided worldwide in 2009, whereas renewable systems received a mere USD 57 billion, the IEA expects this trend to continue.

The technical maturity of a particular technology determines the potential to further refine it – and, consequently, the potential for further cost reductions. Yet there are also technological and operational parameters that limit the potential for cost reductions, despite very good energy yield prospects. For example, take offshore wind turbines: their installation and maintenance are much more costly than that of onshore systems due to the transportation routes and installation conditions. This necessarily results in additional costs which can scarcely be optimised through technical refinement. Yet wind conditions offshore are very good, allowing almost constant electricity supply – and therefore giving the electricity thus produced a higher value. Photovoltaic, and in particular thin-film technology, currently hold the greatest potential for further development.

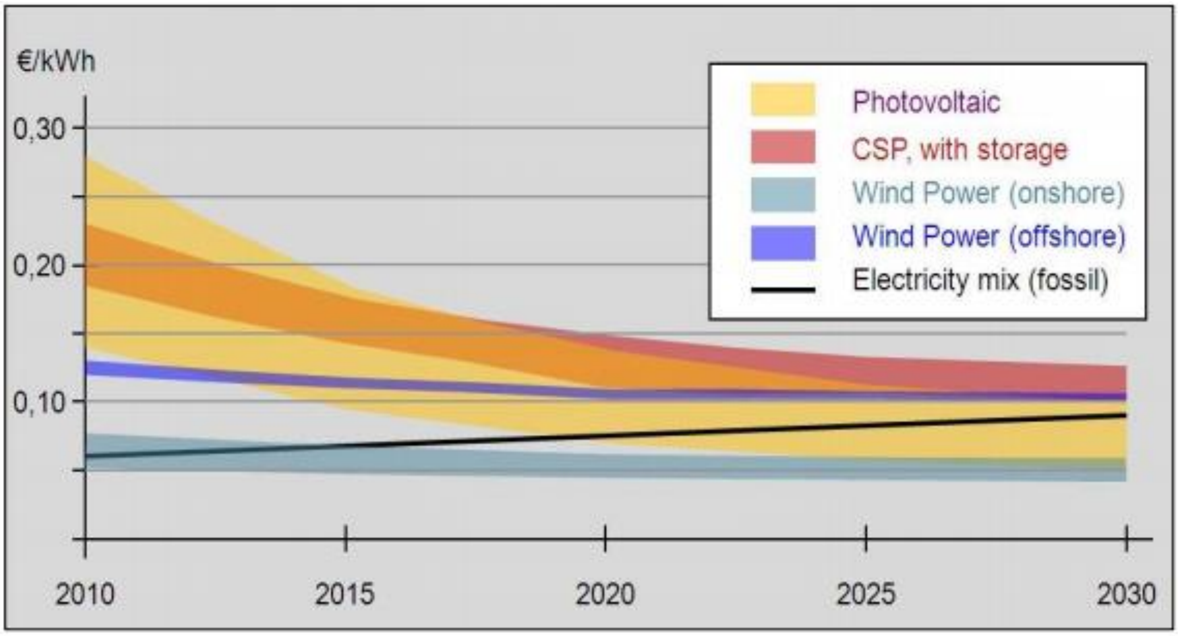


Figure 4: Electricity production cost trends (until 2030) for different renewable energy technologies

3.1 Solar Photovoltaic PV system

Solar photovoltaic technology enables direct conversion of sunlight into electricity through semi-conductor devices called solar cells. Solar cells are interconnected and hermetically sealed to constitute a photovoltaic module. The photovoltaic modules are integrated with other components such as storage batteries to constitute solar PV systems and power plants. Photovoltaic systems and power plants are highly reliable and modular in nature. Solar radiation as intercepted at the earth's surface may be reasonably high in many regions but the market potential for its capture is low due to the current relatively high costs of solar panels. The cost of PV around 5000 USD/kWe installed is slowly falling due to manufacturing scale up and mass production

Table 1
Sustainability indicators for PV systems.

S. no.	Year	Location	Type of cell	Life time (years)	Power rating (kW)	GHG emissions (gCO_{2eq}/kWh_e)	EPBT (years)	Cost (US cent/kWh_e)
1.	2006 [29]	UK	mc-si	NA	14.4	44	8	NA
2.	2000 [30]	India	c-si	20	.035	300	NA	NA
3.	2000 [31]	Italy	c-si	30	3300	60	3.2	NA
4.	2000 [31]	Italy	a-si	30	3300	50	2.7	NA
5.	1997 [6]	Japan	c-si	20	3	91	15.5	NA
6.	2008 [15]	China	c-si	30	100000	12.1	1.9	19–20
7.	2006 [16]	Singapore	c-si	25	2.7	165	4.5	57
8.	2008 [15]	China	c-si	30	100000	9.4	1.5	19–20
9.	2008 [15]	China	a-si	30	100000	15.6	2.5	19–20
10.	1995 [32]	India	c-si	NA	35 kWh_e/m^2	NA	3.95	NA

It is useful to compare costs per unit of energy which is typically given per kilowatt-hour or megawatt-hour. This type of calculation assists policymakers, researchers and others to guide discussions and decision making but is usually complicated by the need to take account of differences in timing by means of a discount rate. The consensus of recent major global studies of generation costs is that wind and solar power are the lowest-cost sources of electricity available total, The study estimate that by 2030 solar electricity could be as cheap as Rs 2.30 per kWh and even cheaper solar costs are possible, in the order of Rs 1.90 per kWh, if the widespread deployment of tracking technology raises the capacity utilization factor of new plants above current levels.

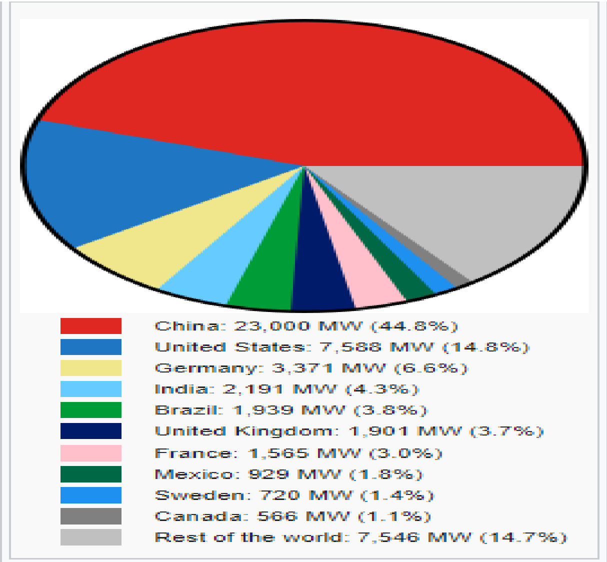
3.2 Wind Energy

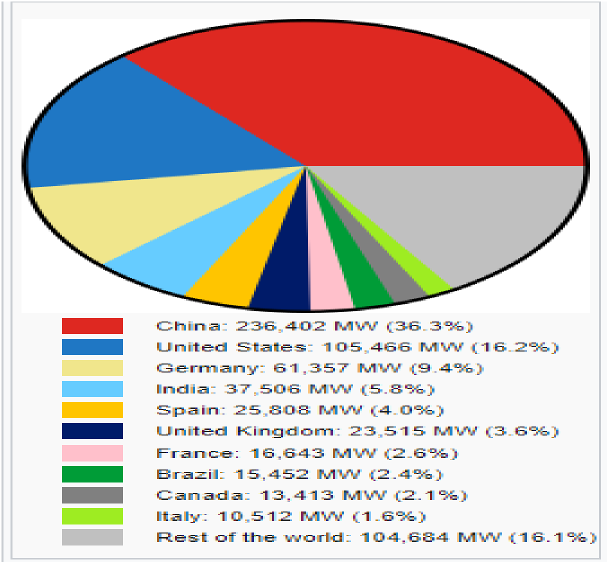
In terms of development, wind power systems have a head start of at least a decade over solar technologies. Wind technology is already available on an industrial scale: this means potential for cost savings here is much smaller than in the newer photovoltaic and solar thermal electricity generation sectors. In contrast with solar installations, wind power necessitates little exclusive (net) land use. It is possible to use land under wind parks for agriculture, almost without restriction. 2.3. Biomass In general, agricultural biogas facilities are only found where regulatory or tax incentives exist for them. Such incentives include strict environmental protection regulations on the discharge and/or treatment of waste substances from cattle farming. Tax incentives for the generation of electricity from biomass may be delivered as investment grants (as in South Africa) or legally guaranteed (feed-in) tariffs as in the German Renewable Energy Sources Act (EEG; e. g. China has followed this model). The cost of investment in agricultural biogas plants varies from project to project and is usually heavily dependent on the technology used for the particular installation. In order to keep investment costs low, the proportion of local production and service input is kept as high as possible in countries with comparatively low wage levels. This local labour can be procured primarily in structural and civil engineering (construction of the fermenter, foundations, access roads, supply pipes etc). However, compliance with time and quality specifications (especially in fermenter construction) must be ensured if the imputed cost savings are indeed to be made. 3. Economic efficiency 3.1. Electricity production costs while in the case of solar installations the irradiation at the site is usually a known value (the solar energy incident on one square metre during the period of one year), the figure used for wind installations is relative. In order to consolidate the electricity generation resulting from the fluctuations in the operation of wind turbines and formulate a reference figure, the concept of annual full load hours is applied. This figure states the (theoretical) number of hours in a year for which a wind turbine generates electricity at full capacity, with the assumption being that the turbine is at a standstill for the remainder of the year. In fact, however, the turbine will operate for much longer periods during any given year, but not at full capacity. The maximum value is the number of hours in a year: 8,760. Conventional plants also 7 never achieve this value due to stoppages for maintenance, repairs, and the like.

Table 2
Sustainability indicators for wind energy systems.

S. no.	Year	Location	Power rating (kW)	Life (years)	EPBT (years)	GHG emissions (gCO_{2eq}/kWh_e)	Cost (US cent/kWh_e)
1.	1997 [22]	Denmark	30	20	0.39	16.5	NA
2.	1996 [23]	Japan	100	20	NA	123.7	NA
4.	1999 [24]	India[a]	1500	20	1.0	19	NA
5.	1996 [25]	UK	6600	20	NA	25	NA
6.	2001 [26]	Japan	100	25	1.4	39.4	NA
7.	2005 [6]	Japan	300	NA	NA	29.5	NA
8.	2007 [27]	Turkey	22.5	25	1.4	20.5	5-74

Wind energy uses the kinetic energy of the wind to produce a clean form of energy without producing contamination or emissions. Wind energy accounts for around 0.3% of the global installed electricity generation capacity due to its relatively recent emergence but due to its intermittent nature, it supplies around only 0.1% of total global electricity the installed capacity of wind power has been rapidly increasing during recent years





a. Top 10 countries by added wind capacity In 2018

b. Top 10 countries by cumulative wind capacity in 2019

3.3 small Hydro and Mini Hydro plant

Hydropower is based on a simple process taking the advantage of the kinetic energy freed by the falling water. In all hydroelectric generating stations, the rushing water drives a turbine, which converts the water's motion into mechanical and electrical energy, The Compact Hydro Division is the world leader in products and services for small and medium-sized hydroelectric power plants and offers also competitive solutions for mini hydro power plants.

Small-scale hydro power plants range up to an unit output of 15 MW for Axial and Kaplan turbines and an output of 30 MW for Francis and Pelton turbines while the mini compact hydro installations include Kaplan and Axial units (20 kW - 1,500 kW), Francis units up to 3,000 kW as well as Pelton units up to 5,000 kW.

Table 3
Sustainability indicators for small hydro systems.

S. no.	Year	Location	Type	Life time (years)	Power rating (kW)	GHG emissions (gCO_{2eq}/kWh_e)	EPBT (years)	Cost (US cent/kWh_e)
1.	1996 [39]	Japan	Run-of river	30	10000	18	NA	NA
2.	2008 [40]	India	Run-of river	30	50	74.88	2.71	NA
3.	2008 [40]	India	Run-of river	30	100	55.42	1.99	NA
4.	2008 [41]	India	Run-of river	30	3000	35.29	1.28	NA
5.	2008 [41]	India	Canal-based	30	250	35.35	1.31	NA
6.	2008 [41]	India	Canal based	30	1000	42.98	1.58	NA
7.	2008 [41]	India	Canal based	30	400	33.87	1.26	NA
8.	2008 [41]	India	Dam-toe	30	2000	31.2	1.1	NA
9.	2008 [41]	India	Dam-toe	30	1000	62.4	2.25	NA

3.4 Solar thermal system

Solar thermal power/electric generation systems collect and concentrate sunlight to produce the high temperature heat needed to generate electricity. All solar thermal power systems have solar energy collectors with two main components, most techniques for generating electricity from heat need high temperatures to achieve reasonable efficiencies. The output temperatures of non-concentrating solar collectors are limited to temperatures below 200°C. Therefore, concentrating systems must be used to produce higher temperatures. Due to their high costs, lenses and burning glasses are not usually used for large-scale power plants, and more cost-effective alternatives are used, including reflecting concentrators. The reflector, which concentrates the sunlight to a focal line or focal point, has a parabolic shape; such a reflector must always be tracked.

Table 4
Sustainability indicators for solar thermal systems.

S. no.	Year of study	Location	Type	Life time (years)	Power rating (MW)	EPBT (years)	GHG emissions (gCO_{2eq}/kWh_e)	Cost (US cent/kWh_e)
1.	1999 [34]	Australia	Central receiver	NA	100	NA	36.2	NA
2.	2008 [35]	Spain	Central tower	25	17	NA	202	NA
3.	1990 [36]	US	Central receiver	30	100	NA	43	NA
4.	2008 [35]	Spain	Parabolic trough	25	50	NA	196	NA

5. Figure of Merit

Figure of merit is generally used to compare the different system based upon their performance, net energy requirement or gross carbon emission from the systems [42–43]. In this paper a FM has been proposed to evaluate the different sustainability indicators on single platform by giving them equal weightage. Accounting FM for the selected sustainability indicators, each technology was ranked from 1 to 10 according to the corresponding indicator as shown in Table 5. The maximum value of particular indicator is assigned to be a relative rank 1 while for minimum value it is assigned to be 10, accordingly the distribution has been done from 1 to 10. The value of GHG emissions, EPBT and cost of electricity generation is lower than their respective relative rank value is assigned to be higher. The range for this relative rank parameter is taken as 1–10 from higher values to lower values of GHG emissions, EPBT and cost of electricity generation. The Eq. (4) is used to estimate FM and is given below.

$$\text{figure of merit} = \text{relative rank Cost} * \text{relatvie rank GHG emissions} * \text{relative rank EPBT}$$

For calculating FM all the data from different renewable energy sources have been taken from the literature. In some literature, all the three indicators values are analysed but these types of studies are very few. In most of the literature either GHG emissions or energy intensity have been analysed and in some of the literature both energy intensity and GHG emissions or EPBT and GHG emissions have been estimated. With the help of energy intensity, energy pay-back time could be estimated by knowing the life time of the electricity generating plant and the average electricity generation efficiency of that particular country where that particular plant lies. The average electricity generation efficiency is taken as 0.40 for the estimation of EPBT from energy intensity. For the determination of figure of merit. Higher the value of figure of merit represents a better renewable electricity generation source. This FM for renewable sources could provide a more rational choice of electricity generation sources for energy planners.

Table 5

Figure of merit for renewable based electricity sources.

S. no.	Year	Location	Source	Type	Life time (years)	Power rating (kW)	Cost (US cents/kWh_e)		EPBT (years)		GHG emissions (gCO_{2eq}/kWh_e)		FM
							Cost	Relative	EPBT	Relative	GHG	Relative	
1.	1997	Denmark	Wind	Offshore	20	30	7	9	0.39	10	16.5	10	900
2.	1999	India	Wind	NA	20	1500	7	9	1.0	10	19	10	900
3.	2001	Japan	Wind	Offshore	25	100	7	9	1.4	9	39.4	9	729
4.	2007	Turkey	Wind	Urban area	25	22.5	7	9	1.4	9	20.5	9	729
5.	2006	UK	Solar PV	mc-si	NA	14.4	24	3	8	2	44	8	48
6.	2000	India	Solar PV	c-si	20	0.035	24	3	1.0	10	300	1	30
7.	2000	Italy	Solar PV	c-si	30	3300	24	3	3.2	7	60	8	168
8.	2000	Italy	Solar PV	a-si	30	3300	24	3	2.7	8	50	8	192
9.	1997	Japan	Solar PV	c-si	20	3	24	3	15.5	1	91	6	18
10.	2008	China	Solar PV	c-si	30	100000	19–20	4	1.9	9	12.1	10	360
11.	2006	Singapore	Solar PV	c-si	25	2.7	57	1	4.5	6	165	2	12
12.	2008	China	Solar PV	c-si	30	100000	19–20	4	1.5	9	9.4	10	360
13.	2008	China	Solar PV	a-si	30	100000	19–20	4	2.5	8	15.6	10	320
14.	1999	Australia	Solar thermal	Central receiver	NA	100	20	4	1	10	36.2	9	360
15.	2006	Spain	Solar thermal	Central tower	25	17	20	4	1.02	9	202	1	36
16.	1990	US	Solar thermal	Central receiver	30	100	20	4	1.04	9	43	8	288
17.	2006	Spain	Solar thermal	Parabolic trough	25	50	20	4	1	10	196	1	40
18.	2008	India	Small hydro	Run-of river	30	50	5	10	2.71	8	74.88	7	560
19.	2008	India	Small hydro	Run-of river	30	100	5	10	1.99	9	55.42	8	720
20.	2008	India	Small hydro	Run-of river	30	3000	5	10	1.28	9	35.29	9	810
21.	2008	India	Small hydro	Canal-based	30	250	5	10	1.31	9	35.35	9	810
22.	2008	India	Small hydro	Canal based	30	1000	5	10	1.58	9	42.98	8	720
23.	2008	India	Small hydro	Canal based	30	400	5	10	1.26	9	33.87	9	810
24.	2008	India	Small hydro	Dam-toe	30	2000	5	10	1.1	9	31.2	9	810
25.	2008	India	Small hydro	Dam-toe	30	1000	5	10	2.25	8	62.4	7	560

Conclusion

Green and sustainable energy technologies has assessed based on three indicators of sustainability. Each indicator has given an equal effect for the sustainable development and particicpate to rank the renewable energy technologies against their impacts and sccores.hance the study indicates that wind energy system and small hydro or mini hydro electricity generation sources are very well friendly for the sustainable development. In case the avilability for those two sourecs is not aplicable then there development may be focused on solar thermal system and solar photovoltaic (PV) systems. However GHG emissions is not only the sustinability parameter to be considered there are many more parameters like land use and water uses may also be included for more exhaustive evaluation of figure of merit. As the invention of new technologies and mass production of these systems will grow, definitely the cost of generation and GHG emissions will go down tremendously. As year of study plays an important role in the figure of merit, initially the cost of generation is higher for these renewable electricity generation sources which are reducing due to advancement in technology and much more efficient systems which are producing.

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