Sustainability of Solar and Wind Energy Sources

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ABSTRACT

The need for energy has increased gradually as human civilization and developments have progressed. Nonrenewable energy resources are those sources, whose formation within the earth takes several millions of years. Renewable energy sources are those take lesser time to replenish the primary energy resource, compared to the rate at which energy is used. Sustainable energy comes from the sources that can fulfil the current energy demands without compromising the need of the future generation. In this paper the different aspects of the sustainability of solar and wind energy sources are discussed. Photovoltaic cells are made from semiconductor materials that transform sunlight directly into electricity. Wind energy is converted to electricity by wind turbines, which use blades to collect the wind's kinetic energy. The blades are connected to a drive shaft that turns an electric generator to produce electricity. Small wind turbine can run at wind speeds as low as two metres per second. They can be connected to the grid or be stand-alone systems and can also be hybridised with solar. They can be mounted even on rooftops. Since offshore wind speeds tend to be about 90% greater than those on land, offshore wind turbines could contribute substantially more energy. Even though the solar energy envisaged as the major sources of renewable energy, they are producing e-waste, which causes environmental problems. Ninety percent of a wind turbine's parts can be recycled but the blades, made of a tough pliable mix of resin and fiberglass are difficult and expensive to transport and disposing in landfill. Much attention should be given to reduce, recycle and reuse of the e-wastes and other wastes from solar energy system and wind turbines so as to make them as sustainable energy sources.

Keywords: Nonrenewable energy; renewable energy; sustainable energy; photovoltaic cells; solar energy system; wind turbine; off-shore wind turbine; Electronic waste; levelized cost of electricity.

I. INTRODUCTION

All developmental activities need energy for the process, operation and maintenances. Further the existence and growth of human communities also need energy. Consequently, the need for energy has increased gradually year after year as human civilization and developments have progressed. There are two types of energy sources, viz., non-renewable energy sources and renewable energy sources. Nonrenewable energy resources are those sources, whose formation within the earth takes several millions of years. Once these resources are used up, they cannot be replaced, hence these sources are collectively called fossil fuels. They include coal, natural gas, oil, and nuclear energy. Today 79% of the world's energy production is from fossil fuels. Renewable energy sources are those take lesser time to replenish the primary energy resource, compared to the rate at which energy is used. Renewable energy sources can always be replenished. The renewable energy sources include hydro power, solar energy, wind energy and biogas

A. Renewable Energy and Sustainable Energy

Renewable energy and sustainable energy are often used interchangeably since many sustainable energy sources are also renewable. However, these two terms are not exactly the same. Renewable energy comes from sources that are naturally renewing themselves at a rate to meet the energy demands. But all the renewable energies are not sustainable. Sustainable energy comes from the sources that can fulfil the current energy demands without compromising the need of the future generation. It involves the efficient collection, transformation and distribution. It includes geothermal, hydropower, solar and wind. It is essential to raise the standard of living of people by providing cleaner and more reliable electricity. The provision of increasing quanta of energy is a vital pre-requisite for the economic growth of a country [1]. India has an increasing energy demand to fulfil the economic development plans that are being implemented. The primary objective for deploying renewable energy in India is to advance economic development, improve energy security, improve access to energy, and mitigate climate change. Sustainable development is possible only by use of sustainable energy and by ensuring access to affordable, reliable, sustainable, and modern energy for citizens [2]. The energy mix throughout the world has changed very quickly as renewable energy has emerged [3,4,5], and energy mix policies must consider many factors, such as economic competitiveness, climate change, public acceptance, safety, and energy security [6]. In this paper the different aspects of the sustainability of renewable energies, in particular solar energy and wind energy are discussed.

II. SOLAR ENERGY

Sunlight is composed of photons, or particles of solar energy, which contain varying amounts of energy that correspond to the different wavelengths of the solar spectrum. Solar energy is environmental friendly technology, a great energy supply and one of the most significant renewable and green energy sources. It plays a substantial role in achieving sustainable development energy solutions [7].

A. Photovoltaic Devices

Solar energy is captured and transformed into electricity through photovoltaic (PV) devices. PV devices, sometimes called solar cells, are electronic devices that convert sunlight into electrical power. Solar, or PV cells are made from silicon or other semiconductor materials that transform sunlight directly into electricity. Inside of the PV cell is shown in Figure 1.

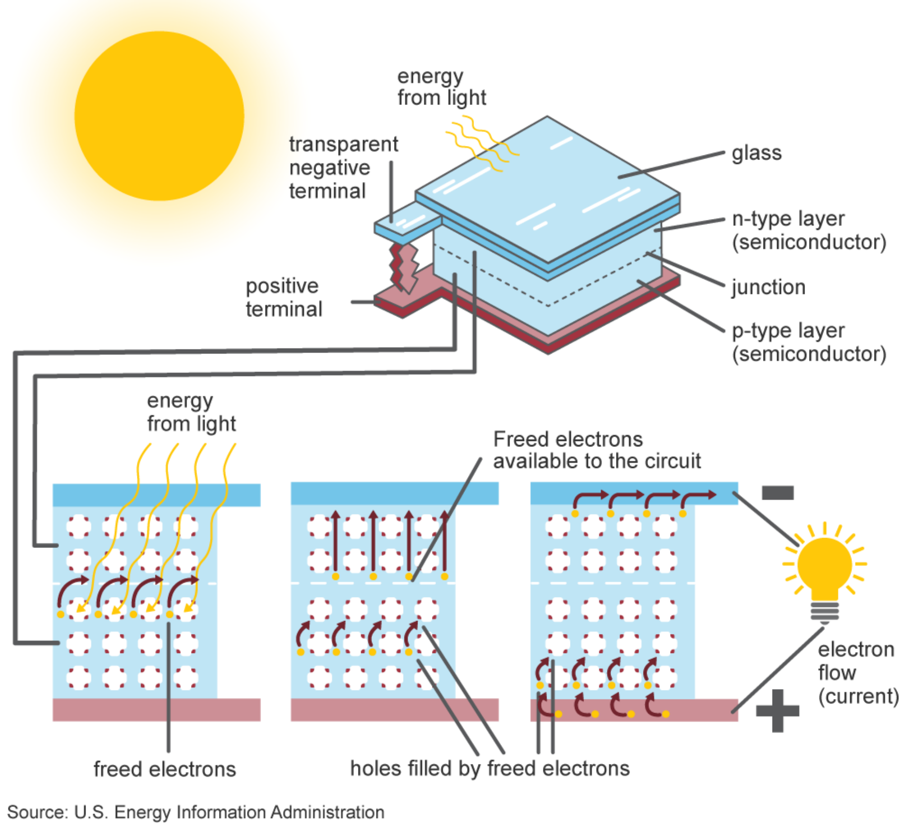

Figure 1. Inside of the photovoltaic cell

The PV cell is the basic building block of a PV system. Individual cells can vary from 12.5 mm to about 100 mm across. However, one cell only produces 1 or 2 Watts, which is enough to supply electricity for small uses, such as powering calculators or wrist watches. PV cells consist of two or more layers of semiconductors with one layer containing positive charge and the other negative charge lined adjacent to each other. Photons of sunlight strikes the cell, where it is either reflected, transmitted or absorbed. When the photons are absorbed by the negative layer of the PV cell, the energy of the photon gets transferred to an electron in an atom of the cell. With the increase in energy, the electron escapes the outer shell of the atom. The freed electron naturally migrates to the positive layer creating a potential difference between the positive and the negative layer. When the two layers are connected to an external circuit, the electron flows through the circuit, creating current.

B. The Flow of Electricity in a Solar Cell

The movement of electrons, each carrying a negative charge, toward the front surface of the solar PV cell creates an imbalance of electrical charge between the cell's front and back surfaces. This imbalance, in turn, creates a voltage potential like the negative and positive terminals of a battery. Electrical conductors on the cell absorb the electrons. When the conductors are connected in an electrical circuit to an external load, such as a battery, electricity flows through the circuit. The power output delivered from a PV module highly depends on the amount of irradiance, which reaches the solar cells. Many factors determine the ideal output or optimum yield in a PV module. Although the efficiency of the PV system has increased through many improvements, there are environmental and natural factors such as the deposition of soil, salt, bird droppings, snow, etc., on the PV module surfaces that can result in inefficiency in the performance of such systems.

PV cells generate direct current (DC) electricity. DC electricity can be used directly to charge batteries that power devices that use DC electricity. Devices called *inverters* are used on PV panels or in arrays to convert the DC electricity to AC electricity. Nearly all electricity is supplied as alternating current (AC) in electricity transmission and distribution systems. Solar PV cells are grouped in panels, and panels can be grouped into arrays of different sizes to power different applications. PV cells and panels will produce the most electricity when they are directly facing the sun. PV panels and arrays can use tracking systems that keep the panels facing the sun, but these systems are expensive. Most PV systems have panels in a fixed position that are usually facing directly south in the northern hemisphere—directly north in the southern hemisphere—and at an angle that optimizes the physical and economic performance of the system.

C. Solar Energy System

Solar energy system consists of solar panel, solar inverter, solar battery and solar stand. The two types of energy system are solar panel connected to battery, called off grid system, and solar panel without battery connected to grid. There are three types of solar panels viz., monocrystalline solar panels, bifacial solar panels and polycrystalline solar panels. In a PV energy system, the solar panel is the main component of the system. All other parts which contribute to the functioning comprise the balance of system (BOS), which include wiring, switches, mounting system, solar inverters, battery bank, battery charger, junction boxes and metring system. In US solar system supplies nearly 3 percent of total electricity generation. But 46 percent of all new generating capacity of electricity came from solar in 2021.

D. Cost of Solar System

On an average the cost of stand alone monocrystalline solar panels is $900 to 1300/kW and grid connected panels is $1000 to 1500/kW; bifacial solar panels is $800 to 860/kW; and polycrystalline solar panels is $710 to 740/kW. In India, monocrystalline solar panels and polycrystalline solar panels are available and their costs for different panel efficiencies are as follows:

- Monocrystalline solar panels

  250 to 300 W capacity
  - 17% efficiency: $577/kWp
  - 18% efficiency: $614/kWp
  - 19% efficiency: $515/kWp
- Polycrystalline solar panels

  0 to 50W capacity
  - 13% efficiency: $785/kWp
  - 14% efficiency: $1079/kWp
  - 15% efficiency: $773/kWp

  150 to 200W capacity
  - 13% efficiency: $638/kWp

  200 to 250W capacity
  - 14% efficiency: $638/kWp

Hence, monocrystalline solar panels are most affordable panels [8].

E. The Efficiency of Photovoltaic Systems

The efficiency at which PV cells convert sunlight to electricity varies by the type of semiconductor material and PV cell technology. The efficiency of commercially available PV panels averaged less than 10% in the mid-1980s, increased to around 25% for state-of-the art modules. Experimental PV cells and PV cells for niche markets, such as space satellites, have achieved nearly 50% efficiency. Solar PV has emerged as a key component in the low-carbon sustainable energy system required to provide access to affordable and dependable electricity, assisting in fulfilling the Paris climate agreement and in achieving the 2030 SDG targets [9].

F. Applications of PV Power

PV cells are one of the rapidly growing renewable energy technologies of today with application in the following fields.

- A PV powered water pumping system is typically used to pump water from wells in rural, isolated and desert areas. The system consists of PV modules to power a water pump to the location of water need. The water-pumping rate depends on many factors such as pumping head, solar intensity, etc.
- A PV-powered cathodic protection (CP) system is designed to supply a CP system to control the corrosion of a metal surface. This technique is based on the impressive current acquired from PV solar energy systems and is utilized for buried pipelines, tanks, concrete structures, etc.
- The smallest PV systems power calculators and wristwatches.
- Larger systems can provide electricity to power communications equipment, supply electricity for a single home or business, or supply electricity to thousands of electricity consumers.
- Distributed solar systems generate electricity locally for homes and businesses, either through rooftop panels or community projects that power entire community. Solar farms can generate enough power for thousands of homes, using mirrors to concentrate sunlight across acres of solar cells.
- Chennai Metro Rail Limited (CMRL) has installed and commissioned a total of 5.2 MW capacity of solar power plants in metro stations and Koyambedu depot. Their target is to install up to 8MW by the end of 2023 [10].

India has an abundance of solar energy to a tune of around 750 GW. Hence, the technology that converts sunlight into electricity and its ecosystem, which is dominated by solar PV, will probably rule the future in this area. There is already a significant thrust by the Government of India (GoI) to install solar panels. According to the Ministry of New and Renewable Energy (MNRE), GoI, India solar power installation has exponentially grown from 0.161 GW in 2010 to 36.9 GW in 2020. According to The Energy Resource Institute's (TERI) study "Transitions in Indian Electricity Sector 2017–2030," India's solar PV installation would cross around 534 GW by 2030 if it is installed in high renewable energy scenarios, and around 161 GW if it is installed in low renewable energy scenarios. The National Centre for Photovoltaic Research and Education (NCPRE) at IIT Bombay was launched in 2010 with funding from the Ministry of New and Renewable Energy (MNRE) of the Government of India. The broad objectives of NCPRE are to provide R&D and education support for India's ambitious 100 GW solar mission [11].

G. Advantages and Disadvantages of PV Cells

Following are the advantages of PV cells [12]:

- PV systems can supply electricity in locations where electricity distribution systems (power lines) do not exist, and they can also supply electricity to an electric power grid.
- PV arrays can be installed quickly and can be any size.
- The environmental effects of PV systems located on buildings is very minimum.
- Solar energy systems don't produce air pollutants or greenhouse gases, and as long as they are responsibly located they have few environmental impacts beyond the manufacturing process.
- PV cells generate clean and green energy as no harmful gases such as CO_x, NO_x etc are emitted. Also, they are environmentally sustainable since they produce no noise pollution which makes them ideal for application in residential areas.
- The installation cost includes only the cost of PV cells and charges for installation. The operation and maintenance costs of cells are very low. Hence they are economically viable.
- Solar panels are easy to set up without interference with public life style.
- They can be made accessible in remote locations or sparsely inhabited areas at a lesser cost as compared to conventional transmission lines.
- Energy is free, abundant in nature and renewable.
- Solar panels have no mechanically moving parts except in some highly advanced system. Consequently, the cost of maintenance and repair of solar panel is negligible.

Following are the disadvantages of PV Cells [13]:

- The efficiency of solar panels is low compared to other renewable sources of energy.
- Energy from the sun is intermittent and unpredictable and can only be harnessed in the presence of sunlight. Also, the power generated gets reduced during cloudy weather.
- Long-range transmission of solar energy is inefficient and difficult to carry.
- The current produced is DC in nature and the conversion of DC current to AC current requires inverters.
- PV panels are fragile and can be damaged very easily. Additional insurance costs are required to ensure a safeguard of the investments.

III. WIND ENERGY

Wind energy is one of the fastest-growing sources of electricity generation—growth that is vital for reducing carbon emissions from electric power. Wind energy is converted to electricity by wind turbines, which use blades to collect the wind's kinetic energy. Wind flows over the blades creating lift, similar to the effect on airplane wings, which causes the blades to turn. The blades are connected to a drive shaft that turns an electric generator, which produces electricity. Total annual U.S. electricity generation from wind energy increased from about 6 billion kilowatt hours (kWh) in 2000 to about 380 billion kWh in 2021.

Small wind energy systems of an individual building can be connected to the electricity distribution system. These are called grid-connected systems. A grid-connected wind turbine can reduce the consumption of utility-supplied electricity for lighting, appliances, electric heating and cooling, and vehicle charging. If the turbine cannot deliver the amount of energy needed, the utility makes up the deficit. When the wind system produces more electricity than the household requires, the excess is credited and used to offset future use of utility-supplied power. Wind power must, therefore, be paired with other generators of equivalent power to compensate for wind variations and for the stability of the electricity grid. This pairing-wind and backup-has limits because of the huge rapid variability of wind that must be compensated for by the backup power source. It is estimated that this pairing can account for only 20 percent of the capacity of the grid

Wind power can be used in isolated off-grid systems, or microgrid systems, not connected to an electric distribution grid. In these applications, small wind electric systems can be used in combination with other components including a small solar electric system to create hybrid power systems. Hybrid power systems can provide reliable off-grid power for homes, farms, or even entire communities that are far from the nearest utility lines. The maximum life expectancy of wind turbines is 20 years with an average of 15years.

A. Small Wind Turbine

As per the International Electrotechnical Commission (IEC), a turbine with a rotor swept area smaller than 200 m^2 that generates 1kW AC or 1.5kW DC power is known as a small wind turbine (SWT) [14]. SWT can run at wind speeds as low as 2m/s. They can be connected to the grid or be stand-alone systems and can also be hybridised with solar. They can also be mounted on rooftops as shown if figure 2, and some of them can be transported from place to place.

Figure 2. Wind turbine on roof top

Certification for SWT is obtained through compliance with the IEC standard numbered 61400–2, last released in 1996. In the 1996 release of the standard, an SWT is defined as any wind turbine with a swept area smaller than 40 m^2 and rotor diameters smaller than 7.0 m across; however, this size restriction is in the process of being relaxed. The IEC standard specifies minimum requirements of an SWT for structural integrity, safety, and other design features in order to ensure safe operation throughout the turbine's intended life [15].

B. Offshore Wind Turbines

Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production, or 40 times current electricity demand. This could require large extent of land for installation of wind turbines, particularly in areas of higher wind resources. Offshore wind speeds tend to be about 90% greater than those on land, so offshore resources could contribute substantially more energy. Most offshore wind farms employ fixed-foundation wind turbines in relatively shallow water as shown in Figure 3. Floating wind turbines for deeper waters are in an earlier phase of development and deployment. As of 2022, the total worldwide offshore wind power nameplate capacity was 64.3GW, China (49%), the United Kingdom (22%), and Germany (13%) account for more than 75% of the global installed capacity [16]. A big advantage of offshore wind power compared to onshore wind power is the higher capacity factor, i.e., an installation of given nameplate capacity will produce more electricity at a site with more consistent and stronger wind which is usually found offshore and only at very few specific points onshore. Corrosion is a serious problem in offshore wind farms and requires detailed design considerations. The prospect of remote monitoring of corrosion looks very promising, Moreover, as power generation efficiency of wind farms downwind of offshore wind farms was found to decrease, strategic decision-making may need to consider cross national limits and potentials for optimization [17].

Figure 3. Offshore wind turbines

C. Cost of Wind Turbine

A modern wind turbine, which can generate two megawatts (MW) of electricity when the wind is blowing, costs about $3.5 million for installation. The O&M cost of a wind farm is approximately 20-25 percent of installation cost. The total cost including operation and maintenance (O&M) of wind turbines and transmission lines of two MW wind energy system could match $4 billion required to build a nuclear plant.

IV. ELECTRONIC WASTE FROM SOLAR ENERGY SYSTEM

Even though the solar energy envisaged as the major alternate source of renewable energy, they are producing electronic wastes (e-waste), which are of much concern. Government of India (GoI) notified the e-Waste (Management) Rules, 2022 for managing the e-waste, which contains rules for management of solar PV modules/panels/cells with the following provisions [18]:

Every manufacturer and producer of solar photo-voltaic modules or panels or cells shall:

i. ensure registration on the portal;
ii. store wastes of solar PV modules or panels or cells waste generated up to the year 2034-2035 as per the guidelines laid down by the Central Pollution Control Board (CPCB) in this regard;
iii. file annual returns in the specified form on the portal on or before the end of the year to which the return relates up to year 2034-2035;
iv. ensure that the processing of the waste other than solar PV modules or panels or cells shall be done as per the applicable rules or guidelines for the time being in force;
v. ensure that the inventory of solar PV modules or panels or cells shall be put in place distinctly on portal; and
vi. comply with standard operating procedure and guidelines laid down by the CPCB in this regard.

Twenty-one metals present in e-waste from solar energy system are classified with respect to their economy and weight share. Based on the solar potential share of each state and the existing recycling infrastructure, India is divided into six clusters for end-of-life (EOL) waste collection. India can expect 295 million tonnes of waste from EOL solar PV and its BOS in the next 25 years. 70 percent of the e-waste could be recovered. As the quantity of EOL solar PV e-waste is comparatively higher than other e-waste, because of its abundant metals and toxic materials, which causes problems for the EOL disposal of solar PV e-waste. To manage EOL solar PV wastes generated in developing countries, material flow analysis has been used as per requirement of a circular economy for designing, recycling, remanufacturing and refurbishing strategy and assessment of resource efficient regulations. It would help policy makers to develop afresh policies [19].

Today, India ranks 4th in the world in installed renewable energy capacity. India's nonfossil fuel energy has reached 40% of the country's energy mix. The 26th session of the Conference of the Parties (COP 26) to the UNFCCC was held in Milan from 30 September to 2 October 2021. The COP-26 meeting has come up with a speaking statement toward massive use of solar power in the coming days. Accelerating the transition from coal to clean power is a key focus of the COP26 [19]. The power sector accounts for a quarter of global greenhouse gas emissions and, to meet the goals of the Paris Agreement, there is a need to move away from coal and towards clean power at about five times faster than at present. There are many big opportunities available for renewable energies as generating power using solar and wind is now cheaper than burning coal in most countries. This would create a serious concern for creating a robust infrastructure for reduce, reuse, disposal of EOL solar PV [20].

V. PERFORMANCE ANALYSIS OF PV PANEL

The rate of peak power generation of a PV panel in the afternoon of sunny day is expressed in kilo Watt peak (kWp). For example PV panels with peak power generation of 250kWp working at maximum capacity for one hour will produce 270kWh electricity. The performance analysis of a 190 kWp solar PV power plant installed at Khatkar-Kalan, India, was carried out [21]. The final yield, reference yield and performance ratio from the analysis are found to vary from 1.45 to 2.84 kWh/kWp-day, 2.29 to 3.53 kWh/kWp-day and 55–83% respectively. The annual average performance ratio, capacity factor and system efficiency are found to be 74%, 9.27% and 8.3% respectively. The average annual measured energy yield of the plant is found to be 812.76 kWh/kWp. The average annual predicted energy yield is found to be 823 kWh/kWp using PVsyst model . The estimated energy yield is in close agreement with measured results with an uncertainty of 1.4%. The total estimated system losses due to irradiance, temperature, module quality, array mismatch, ohmic wiring and inverter, are found to be 31.7%. According to a study the solar energy generated is maximum during March, September, and October and minimum in January.

VI. LEVELIZED COST OF ELECTRICITY

The levelized cost of electricity (LCOE) is used widely to compare the economic competitiveness of the energy mix. This method is easy to understand and simple to apply, which makes it preferable for many energy policymakers. However, the method has several disadvantages from the energy business perspective. First, the LCOE approach does not consider revenue, and a high-interest rate usually correlates with the tariff growth rate. Thus, if a high-interest rate increases the cost and revenue, which can affect economic competitiveness. Second, the LCOE does not consider different stakeholders. Equity investors and loan investors have different interests depending on different financial indicators, which influence the same energy sources' differential economic attractiveness [22]. LCOE, which is adopted as a metric to estimate power generation technologies' competitiveness [23,24]. The LCOE is an indicator used widely, in that it can compare different lifecycle energy sources easily [25]. The LCOE is a widespread indicator used to compare cost competitiveness and identify the grid parity among different energy generation technologies [26]. It presents the unit cost of constructing and operating a generating plant over the assumed project life. The LCOE value usually is calculated as total lifetime cost divided by total lifetime energy production [27].

The global weighted average LCOE of new onshore wind projects added in 2021 fell by 15%, year on year, to $0.033/kWh, while that of new utility-scale solar PV fell by 13% year-on-year to $0.048/kWh and that of offshore wind declined 13% to $0.075/kWh. With only one concentrating solar power (CSP) plant commissioned in 2021, the LCOE rose 7% year-on-year to $0.114/kWh. The period 2010 to 2021 has witnessed a seismic improvement in the competitiveness of renewables. The global weighted average LCOE of newly commissioned utility-scale solar PV projects declined by 88% between 2010 and 2021, whilst that of onshore wind fell by 68%, CSP by 68% and offshore wind by 60%. [29]

As the burning of fossil fuels accounts for 87% of the world's CO_2 emissions, a world run on fossil fuels is not sustainable, they endanger the lives and livelihoods of future generations and the biosphere around us. And the very same energy sources lead to the deaths of many people *right now* – the air pollution from burning fossil fuels kills 3.6 million people in countries around the world every year; this is *6-times* the annual death toll of all causes combined with murders, war deaths, and terrorist attacks.

VII. WASTES FROM WIND TURBINES

Ninety percent of a wind turbine's parts can be recycled or sold, but the blades, made of a tough but pliable mix of resin and fiberglass, similar to material from which spaceship parts are made. "The blades are kind of a dud because they have no value. Decommissioned blades are also notoriously difficult and expensive to transport. They can be anywhere from 30 to 100 metre long and need to be cut up onsite before getting trucked away on specialized equipment, which costs money to the landfill.

A. Opportunities for Reuse and Recycling

Building wind turbines requires large quantities of materials and components. These components will eventually reach the end of their design lifetimes and could go to landfills, unless innovation provides an answer. Using, reusing, recycling, and remanufacturing wind turbine materials will reduce waste and create a circular economy, which means that technology should be engineered from the start to require fewer materials, resources, and energy while lasting longer and having components that can easily be broken down for use in subsequent applications. Of the wind, solar and other renewables that came on stream in 2020, nearly two-thirds, 62%. According to the International Renewable Energy Agency (IRENA) renewable energies were cheaper than the cheapest fossil fuel [30].

VIII. CONCLUSION

Wind power's advantage over solar panels is that turbines work at night and even when there are just mild winds. The installation of wind energy costs around one to $0.75million depending on the technology providing company, the scale of plant, and other factors, a tax break of 80% is available as depreciation for the first year. The operation cost, including insurance, costs $490 to 615 every year. In India the current rate of solar panel installation is around $86/kW and the maintenance and operating costs of solar panels are comparatively less. Further Government subsidies will also be available. Wind turbines convert around 50% of captured wind energy into electricity, whereas the conversion rate of sunlight by solar panels stands at approximately 23%. Looking at this, we can conclude that wind energy is twice as efficient as solar panels.

DISCLOSURE STATEMENT

The author declares that he has no known competing financial interest or personal relationship that could have appeared to this paper.

REFERENCES

1. Charles Rajesh Kumar. J and M. A. Majid, "Renewable energy for sustainable development in India: current status, future prospects, challenges, employment, and investment opportunities", *Energy, Sustainability and Society* , 2020, volume 10 (2).
2. Charles Rajesh Kumar. J, Vinod Kumar, and D.M.A. Majid "Wind energy programme in India: emerging energy alternatives for sustainable growth". Energy & Environment, 2019, 30(7):1135-1189.
3. M. Bilgili, A. Ozbek, B. Sahin, and A. Kahrama,. "An overview of renewable electric power capacity and progress in new technologies in the world". *Renew. Sustain. Energy Rev.* 2015, *49*, 323–334
4. C. Budischak, D.Sewell, H.Thomso, L.Mach, D.E.Veron, and W.Kempton, "Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time". *J. Power Sources* **2013**, *225*, 60–74.
5. M.Z.Jacobson, and M.A.Delucchi, "Providing all global energy with wind, water, and solar power, Part I: technologies, energy resources, quantities and areas of infrastructure, and materials". *Energy Policy* **2011**, *39*, 1154–1169.
6. T.Bruckner, I.A.Bashmakov, Y. Mulugetta, and H. Chum, A. de la Vega Navarro, J. Edmonds, A. Faaij, B. Fungtammasan, and A.Garg, "Mitigation of climate change" Energy Systems, Chapter 7, 2014
7. Ali, O.M.Maka, and Jamal M.Alabid, "Solar energy technology and its roles in sustainable development" . *Clean Energy*, Volume, 2022, 6, 476–483.
8. https://economictimes.indiatimes.com/small-biz/productline/power-generation/solar-panel-cost-price-range-of-different-types-of-solar-panels accessed on 29.7.23
9. C.Parrado, A. Girard, F. Simon, and E. Fuentealba, "2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile". *Energy* **2016**, *94*, pp 422–430.
10. https://www.newindianexpress.com/cities/chennai/2019/aug/28/solar-power-plant-set-up accessed on 29.7.23.
11. https://rnd.iitb.ac.in/node/101501 accessed on 28.7.23
12. https://www.eia.gov/energyexplained/solar/photovoltaics-and-electricity.php accessed on 22.7.23
13. https://byjus.com/physics/solar-energy-and-photovoltaic-cell/ accessed on 22.7.23
14. https://en.wikipedia.org/wiki/IEC_61400, accessed on 27.7.23
15. IEC 61400–2 ed.1, "Wind Turbine Generator Systems – Part 2: Safety of Small Wind Turbines", International Electrotechnical Commission (IEC), 1996.
16. M. Hutchinson, Mark, Zhao, and Feng, "Global Wind Report 2023" Global Wind Energy Council.2023, pp. 8, 99.
17. Akhtar, Naveed; Geyer, Beate; Rockel, Burkhardt; Sommer, S.Philipp Schrum, Corinna; "Accelerating deployment of offshore wind energy alter wind climate and reduce future power generation potentials". Scientific Reports, 2021 11 (1): , doi:10.1038/s41598-021-91283-3.
18. Ministry of Environment, Forest and Climate Change, government of India, E-Waste (Management) Rules, 2022, SO360(E).
19. A. Gautam, Ravi Shankar, and Prem Vrat, "Managing end-of –life solar photovoltaic e-waste in India: a circular economy approach", Journal of Business Research, 2022, 142, pp 287-300.
20. https://www.lboro.ac.uk/news-events/news/2021/november/solar-energy-importance-cop26-explainer-video/ accessed on 25.7.23
21. Vikrant Sharma, and S.S.Chandel, "Performance analysi of a 190kWp grid interactive solar photovoltaic power plant in India", Energy, 55, 2013,pp 476-485.
22. Sanghyun Sung, and Wooyong Jung, "Economic competitiveness evaluation of the energy sources: comparison between a financial model and levelized cost of electricity analysis", Energy, 12(21) 2019, 4101; https://doi.org/10.3390/en12214101
23. K. Branker, M.J.Pathak, and J.M.Pearce, "A review of solar photovoltaic levelized cost of electricity". *Renew. Sustain. Energy Rev.* 2011, *15*, pp 4470–4482.
24. U.Nissen, and N.Harfst, "Shortcomings of the traditional levelized cost of energy [LCOE] for the determination of grid parity". *Energy* 2019, *171*, pp 1009–1016.
25. K.J. Benes, and C.Augustin, "Beyond LCOE: A simplified framework for assessing the full cost of electricity". *Electr. J.* 2016, *29*, pp 48–54.
26. J. Loewen, "LCOE is an undiscounted metric that distorts comparative analyses of energy costs". *Electr. J.* 2019, *32*, pp 40–42.
27. Tran, T.T.; Smith, A.D. Smith. Incorporating performance-based global sensitivity and uncertainty analysis into LCOE calculations for emerging renewable energy technologies. *Appl. Energy* 2018, *216*, pp 157–171.
28. A.Tolis, A.Doukelis, and I.Tatsiopoulos, "Stochastic interest rates in the analysis of energy investments: Implications on economic performance and sustainability". *Appl. Energy* 2010, *87*, pp 2479–2490.
29. https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 accessed on 22.7.23.
30. https://www.weforum.org/agenda/2021/07/renewables-cheapest-energy-source/ accessed on 22.7.23