

Life cycle assessment on onshore wind farm: An evaluation of wind generators in India

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ABSTRACT

Wind energy is chosen as one of the most important clean energy sources for today's world. It hardly generates any emissions during its operational time. Most of the emissions on wind technologies are associated with its different material manufacturing, transportation, installation. To calculate these emissions, LCA is used to find out the environmental impact of wind farms from the same wind class. The main aim of this paper is to compare the environmental impact/benefit of different wind turbine-generator sets used in the wind farm using cradle-to-grave method by Life Cycle Assessment tool. For this, two different types of turbine-generator-based wind farms are chosen from Karnataka, India, and a comparison has been done by considering whole life cycles of them. Then, the sensitivity analysis is carried out to find out the affect of wind speed on LCA methodology. The result highlighted that both the mentioned turbine-generator-based wind farms are suitable for wind power technologies, but Asynchronous generator-turbine based wind farm emits comparatively low emission as compared to respective size and its required less energy return time. This paper also newly revealed that increased wind speed has trends to increase Environmental Effective Elements Emission through LCA.

Introduction

To decrease carbon footprint and to secure our future, wind energy is chosen as the fastest-growing energy source of the globe [1]. In India, wind energy is growing extensively due to its modernized technologies and high range of deployment capacities [2]. It is found from the study that yearly installed cumulative wind power capacity is exponentially increasing globally. For it, India becomes fourth among the world [3]. As the yearly installed cumulative wind power capacity is rising, wind turbine manufacturing as well as rising over the world. These wind turbines started their journey from few kW productions and today it reached to multi-MW production [4]. From 40 kW in the 1980's, the installed wind power capacity of India reaches to 40 GW in 2021 [5]. The government of India announced almost 60GW wind power generation by 2022 [6]. Fig. S1 (Supplementary material) shows the increment in installed wind power capacity of India from 1980 to 2022 [7]. This figure gives an idea about how wind power capacities throughout the country are increasing rapidly. It is noticeable that, within 30–35

years, installation capacities of wind farm increased rustically due to its environment friendly behavior. To generate more power from wind energy, the generator plays a most vital role in the turbine set. The standard average ratings of commercial wind turbine-generator is started from 1.5 MW. All these installed wind turbines are primarily characterized as geared and non-geared generators [8]. Low-speed non-geared wind generators are directly connected with the turbine hub, whereas high-speed geared wind generator converts normal rotor speed into the rotational high speed [9]. The most popular option for the non-geared generator is Synchronous Generators (SG) and Asynchronous Generators (AG) are chosen for geared generators nowadays. Direct Drive Synchronous Generator (DDSG) based turbine sets face a different type of failure as it is directly connected to the rotor hub. To overcome such problems in DDSG, the permanent magnet is used in the place of the field coil. Therefore, Permanent Magnet Synchronous Generator (PMSG) type turbine sets are preferable in the case of the gearless option [10]. Besides, if we focused on AGs, Fixed Speed Induction Generator (FSIG) based turbines are not suitable options for wind technologies as it runs at

Abbreviations: AG, Asynchronous Generator; DDSG, Direct Drive Synchronous Generator; DFIG, Doubly Fed Induction Generator; EEEE, Environmental Effective Elements Emission; ERT, Energy Return Time; FSIG, Fixed Speed Induction Generator; LCI, Life Cycle Inventory; LCIA, Life cycle Impact Assessment; IEC, International Electrotechnical Commission; ISO, International Organization for Standardization; PDD, Project Design Document; PMSG, Permanent Magnet Synchronous Generator; SG, Synchronous Generator.

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a stable speed and their outcome is limited [11]. But, in Doubly Fed Induction Generator (DFIG) based turbine set, a normal rotor speed is converted to high rotational speed and thus the output power becomes more [12]. DFIG turbine can run at any low wind speed so DFIG turbine-based wind farm gives continuous power. DFIG-based turbine set gives more faster response as most of the DFIGs are controlled by the power converter that is connected to the rotor terminal. Among all types of generators, DFIG turbines are most preferable for wind technologies [8,9]. In 2019, more than 70 % of AG's turbines and less than 20 % of SG's turbines are installed in India [13].

Here, we focused on some previous research papers for literature that had only focused on generators used in wind turbines. In 2009, Martinez et al. aimed to find out the overall lifetime environmental effect of the wind power plant. Here, SimaPro 7.0 Pre Consultants software is used to find the environmental effect of the DFIG turbine set. Environment pollution from different stages can be recovered by less than one year is shown in their result [14]. Guezuraga et al. identified the environmental impact of two different wind turbines (geared and non-geared) and compared them with PV plant, Hydro plant, Nuclear plant, the coal-fired power plant in 2012. GEMIS software is used to compare the various effect on the environment. The result showed the environmental impact and the energy payback time is less for the wind turbines as compared to the other power plants [15]. In 2015, Lloberas-Valls et al. compared two different types of wind turbines using LCA for verifying environmental effects. GaBi 6 software is used to compare two different offshore wind turbines. As result, they found second-generation high-temperature superconductor direct-drive SG has less environmental effect as compared to direct-drive PMSG [16]. MartÁnez et al. explored the environmental profit of repowered wind farms using LCA in 2018. They choose SimaPro 7.0 software for their analysis. A repowered wind farm can run almost triple lifetimes as compared to the original wind farm. The DFIG-based repowered wind farm is more profitable, this result is shown in their work [17]. Repowering is good if an efficient wind speed is available. In 2019, Schreiber et al. analyzed the environmental impact of different generators used in wind mill's turbines set using LCA. They choose GaBi 8.7 software for their analysis. As result, it is mentioned that SGs are more environmentally impactful and Energy Return of Investment (EROI) is more in SGs as compared to IGs [18]. But they don't properly focus on wind speed. Overall, different research papers have mentioned about different scenarios of turbine-generators sets with LCA but they don't clearly mention the relation of different turbine-generator set with the wind speed and their impact on the environment through LCA.

Life Cycle Assessment helps to develop the use of the different efficient products and the idea of the environmental impact of different turbine-generator sets used in various power plants [19]. LCA is a tool for analyzing the environmental impact of any product. From material production, material transportation, construction, maintenance, and end of life, LCA takes all the life-sections for finding the environmental effect of the turbine-generator set [20]. For sustainable energy development, LCA helps researchers to find the future path. LCA consists of four different stages and it takes different LCA-methods to calculate the environmental effect [21]. This study has been carried out as per the ISO 14040/14044 standard. Therefore this research paper focuses on:

- i) Different types of the generator-turbine-based wind farm for LCA calculation and their comparison.
- ii) To calculate environmental effective elements emission (EEEE) through LCA and comparing, an asynchronous generator-turbine (AG) based existing wind farm and synchronous generator-turbine (SG) based assumed wind farm are taken. These two AG and SG based wind farms for the same location are taken by following the IEC standard wind class.
- iii) To make a connection between EEEE and wind speed, and to find LCA's potential environmental impact/benefit, the wind speed is considered in every life section of the wind farms.

For these above aspects, a case study is done in the selected location is in between Shimoga and Chitradurga district of Karnataka, India. The objective of this research paper is to find out the potential environmental impact/benefit from wind farms by considering wind turbine-generator types and wind speeds. Existing environmental impact studies by LCA for the wind farm have either focused on wind turbine types or patterns of wind. But no combinational studies have been found for LCA where wind speed and generators pattern are taken into account.

Therefore, this paper is organized as, section 2 gives a brief discussion about the technical route and LCA methodology, section 3 gives technical information about this paper, section 4 draws results and discussion lines. Thus section 5 presents the conclusion of this paper.

Methodology

Technical route

Taking the concept of LCA and the function of the generator on a wind turbine, we combined the LCA with wind generators which depend on wind speed. The combinational logical structure of LCA in relationship with wind generator and wind speed is shown in [fig. S2 \(Supplementary material\)](#). [Fig. S2](#) is explaining that when the wind hits the turbines, the turbine-generator sets produce power. Here, wind speed is taken as the input as wind speed varies from time to time, and turbine-generator set boxes are also taken as the input for further use of the different types of generator-turbine sets. Noticed, only SG and AG based wind farms are considered here. Power output boxes are required to check the power variation due to the change in both the inputs. Now, the LCA has performed on both the SG and AG based wind farms and the output of it may be environmentally effective or beneficial. Now, a comparison has been done between the results of the SG and AG based wind farm's LCA to check which is more preferable.

LCA framework

To measure, analyze and identify the environmental impact from various products or systems during its whole lifetime, LCA is a well-known method. LCA follows the general guidelines given in ISO 14040/14044 standard. Based on this ISO standard, the calculation of environmental effective elements emission from the wind farm for its whole lifetime includes four research stages [22,23]. They are:

Life cycle Inventory analysis (LCI): It collects the input and output data for each stage of the life cycle system [24].

Life cycle Impact Assessment (LCIA): This stage helps to find out the environmental impact and to investigate impact categories associated with input and output.

Interpretation: It concludes the whole process by combining LCI and LCIA as per goal and scope definition. The pictorial representation of LCA stages is shown in [fig. S3 \(Supplementary material\)](#).

Goal and scope

The first stage of LCA defines the system boundaries and its functional unit [25]. The goal of this paper is to find out and compare the environmental impact of different types of generators used in wind turbines and their relation with wind speed. As per author's knowledge, no such work has been found in previous studies. Overall, this paper shows a clear relationship between turbine-generators types and wind speed for LCA operation.

Life cycle Inventory (LCI)

Data is taken from the renowned wind turbine manufacturers and some research papers which are used for the materials in construction of AGs and SGs based wind farms [26,27,29]. To find out the environmental effective elements emission source and its emission path by LCA, this paper has four different sections: material production section,

material transportation section, construction, and maintenance section, and end-of-life scenario section. As the data for SG based turbine-generator set is not available for selected location of India, material production, construction and maintenance, and end-of-life data is taken from reference [27] and transportation data is taken as assumption-based verbal communication. The total EEEE from different life cycle sections is calculated by:

$$LCA_{EEEE} = EEEE_{MP} + EEEE_T + EEEE_{C\&M} + EEEE_{EoL}$$

where LCA_{EEEE} indicates the total amount of environmental effective elements emission during the whole life cycle of the wind farm, $EEEE_{MP}$ denotes environmental effective elements emission during material production, $EEEE_T$ denotes environmental effective elements emission during transportation, $EEEE_{C\&M}$ denotes environmental effective elements emission during construction and maintenance and $EEEE_{EoL}$ denotes environmental effective elements emission during the end of life process. The symmetrical diagram of total environmental effective elements emission through LCA is shown in [fig. S4 \(Supplementary material\)](#). Here, blank arrows are showing jumping to the next sections.

Life cycle impact Assessment (LCIA)

In this stage, all the inputs and outputs data of the LCI converts into the special outcome in which potential environment impact/benefit has been calculated. LCIA is conducted by using the different problem-oriented categories to find out the environment impact/benefit. It is performed to analyze energy consumption and resource calculation, to evaluate environmental impact/benefit for the all life cycle sections of the wind farm, and to find out energy payback time and energy payback ratio of both the SG and AG based wind farm by considering wind speed [30]. CML 2001 baseline category for potential environment impact/benefit assessment developed by the University of Leiden, Netherland is used in this paper [36,37]. This impact assessment category shown in [table S1 \(Supplementary material\)](#):

Interpretation

According to the goal and scope definition of the system, LCI and LCIA are interpreted in this stage. By considering all the life cycle sections, this stage recognizes the elements that provide the most contribution for LCA calculation and it checks whether this result is meeting with the goal and scope definition of the paper or not. Moreover, this section provides a clear scenario about the limitation of the paper and shows a brief relationship picture between the environmental impact and safety limit [23,31].

Case study

Technical information

For case study analysis, the 56.1 MW existing onshore wind farm in between Shimoga and Chitradurga district of Karnataka, India is used to analyzing and discussing the environmental impact/benefit from the wind farm. This wind farm has 34 AG-turbine-based wind turbines with an individual capacity of 1.65 MW. The basic information about the existing AG-turbine-based wind farm is given in Table 2. All the data are taken from PDD and reference [32]. As the wind speed is not the same throughout all the year, so power outcome varies in the power curve. [Fig. S5 \(Supplementary material\)](#) shows the monthly average wind speed variation of selected locations with their existing wind farm's power curve [29].

Since SG-turbine-based wind farm does not exist in this area, SG-turbine-based wind farm has been assumed for comparison. Follow [table S2 \(Supplementary material\)](#) for technical specifications of assumed SG-based wind farm. All these data are assumed for 140 GWh/year clean power supply to 35,000 Indian homes. These two types of wind turbine-generator are chosen under variable speed – variable

frequency (VSVF) scheme [34]. [Fig. S6 \(Supplementary material\)](#) shows the geographical view of the selected location. In the figure right side is showing satellite view and the left is pointing the area.

For this, the following assumptions and original data are taken to analyzing and discuss the environmental impact/benefit:

1. All the components or elements used in the material production of SG-turbine set-based wind farms are taken from reference [27,28].
2. As the onshore wind farm is installed in the land, the transportation data are assumed from verbal communication and some from the references [26,27,28,33].
3. In most of the onshore installation and maintenance cases, the energy and fuel consumption are almost the same, so construction and maintenance are chosen from [27,28].
4. For the end-of-life case, data is taken from the [27,28] reference.

Material production

For the production of different materials such as wind turbine-generator components, raw materials like steel, aluminum, iron, copper, oil, etc conventional elements are used. In the case of AGs, uses of the conventional elements are more as compared to SGs because of gear. But AG based wind farm gives more power as they can run at low wind speed. The main objective of this section is to calculate total input energy and raw material used during the production and manufacturing of different wind turbine materials and to find out the total amount of environmental effective elements emission. This section is responsible for the highest amount of EEEE. [Table S3 \(Supplementary material\)](#) shows Components used for AG-based and SG-based Wind Turbines.

Transportation

To shift the main materials for the wind farm from the production side to the installation side, a carrier: transportation took an important rule [35]. Considering the geographical position, if the distance between production side and installation side is not long, land transport means road or rail transport are used. If the distance is long, sea transport is used to take the materials. This section calculates the total fuel used as input and total amount of environmental effective elements emission during transportation. It occupied the third position in the case of EEEE.

Construction and maintenance

This section consists of installation or construction of each part of the wind farm, its operation, and maintenance. Most importantly, bidirectional energy is found in this section as it gives wind power. From the concrete, sand, stone, this section uses natural gas, diesel, gasoline, etc as its input. This section is responsible for second-highest amount of EEEE. The total amount of different forms of energy used as input and total amount of environmental effective elements emission during construction, operation, and maintenance of wind farm are evaluated in this section.

End of life scenario

After the life, some of the materials used in the wind farm are recycled, some of them are incinerated and some of are used as land filled, further disposed [31]. The input energy is required for recycling or incineration or landfill. The rate of recycling the material is more at the end-of-life scenario because most of the first installed wind farms part stayed operational after its first live use. The landfill process is taken because some materials like resin are not suitable for recycling, and some materials like plastic are incinerated. [Table S5 \(Supplementary material\)](#) shows end-of-life scenarios of different materials used in Wind Farm. But EEEE is present from recycling to disposal, all the time. For further clarity, [fig. S4](#) shows every section of LCA of a wind farm.

Functional unit

The functional unit is important as it is used to identify the total amount of environmental effective elements emission during per kWh of electricity production. Table S4 (Supplementary material) indicates some important LCI emission factors for 1 kW electricity yield for both the wind farms. The production of 1kWh of electricity from the wind farm is considered as functional unit for this LCA study. By connecting the functional unit, all the LCI input and output data are taken during LCA studies. The functional unit of the wind farm can be calculated by:

$$FU_{LCA} = LCA_{EEEE} / WP_{kWh} \quad (1)$$

Here, FU_{LCA} indicates the functional unit of the wind farm. LCA_{EEEE} is representing the total amount of environmental effective elements emission. WP_{kWh} indicates wind power in kWh [44].

Sensitivity test

Here, the sensitivity test is carried out to identify which turbine-generator set is emits more environmental effective elements and takes more energy return time (ERT) during its whole life cycle by considering wind speed. Basically, the sensitivity test determines how the input can affect the output of the system that means is any small change in input can change the output? If yes, then the system is firmly sensitive to its input.

Results and discussion

Analysis of EEEE intensity

The entire wind farm has an impact on the environment from its materials production to life-end. Based on the different sections of the wind farm, first, EEEE is calculated followed by LCA protocol. As wind power technology is the most environment-friendly technology, its emission factors are very low [37], but still there is some EEEE in every section of the wind farm's life cycle. Fig. 1 shows the calculated total EEEE of AG-based existing and SG-based assumed wind farm of Mahadevapura area, Karnataka, India.

Fig. 1 clearly shows SG-based wind turbine has more environmental impact than AG-based wind turbine. First of all, all the impacts results are added together and after adding, contribution of each group has been separated. The percentage configuration of each impact group of wind farms shows their own contribution. These percentage results are taken for easy identification of contribution of each impact group. In each impact group, the contribution of SG-based wind turbine is highest except Abiotic Resource Depletion. In Abiotic Resource Depletion impact group, AG-based wind turbine contributes 0.05 % from total, whereas SG-based wind turbine contributes 0.005 % from total. But still, it has very little difference. SG-based wind turbine shows its highest EEEE in Climate Change (40 % from total contribution of SG-based wind turbine) followed by Acidification Potential (37.8 % from total contribution of SG-based wind turbine), Human Toxicity (11.7 % from total contribution of SG-based wind turbine), Eutrophication Potential (10.4 % from total contribution of SG-based wind turbine), Photochemical oxidation (1 % from total contribution of SG-based wind turbine), and Abiotic Resource Depletion (0.005 % from total contribution of SG-based wind turbine) [39].

If we hardly focus on impact groups, Climate change, due to the extreme increase of greenhouse gases, global temperature is rising and it can cause climate disturbance, rising in sea level, land degradation, even spreading of disease [40]. After that, acid gas like Sulfur dioxide is responsible for acidification that can damage the eco-system and biodiversity. Chemical reaction of hydrochloric elements with the environment is the cause of human toxicity. It can be the reason for cancer; can damage the respiratory system of living beings [41]. Nitrogen oxide is the reason of eutrophication which can destroy the eco-system. Photochemical oxidation happens due to the reaction of carbon monoxide, sulfur dioxide, nitrogen oxide, and NMVOC in presence of heat and it can cause the imbalance relationship between living beings and the environment [42]. Consumption of natural resources like water, fossil fuel, minerals, etc. creates Abiotic Resource depletion and it can cause scarcity of resources [43].

Calculated EEEE during the whole life cycle of AG-based existing 56.1 MW and SG-based assumed 57 MW Wind Farm is shown in Fig. 2. This figure shows section-wise EEEE of Wind Farms for 1 kW electricity yield. Here, the Material Production section of each wind farm has the

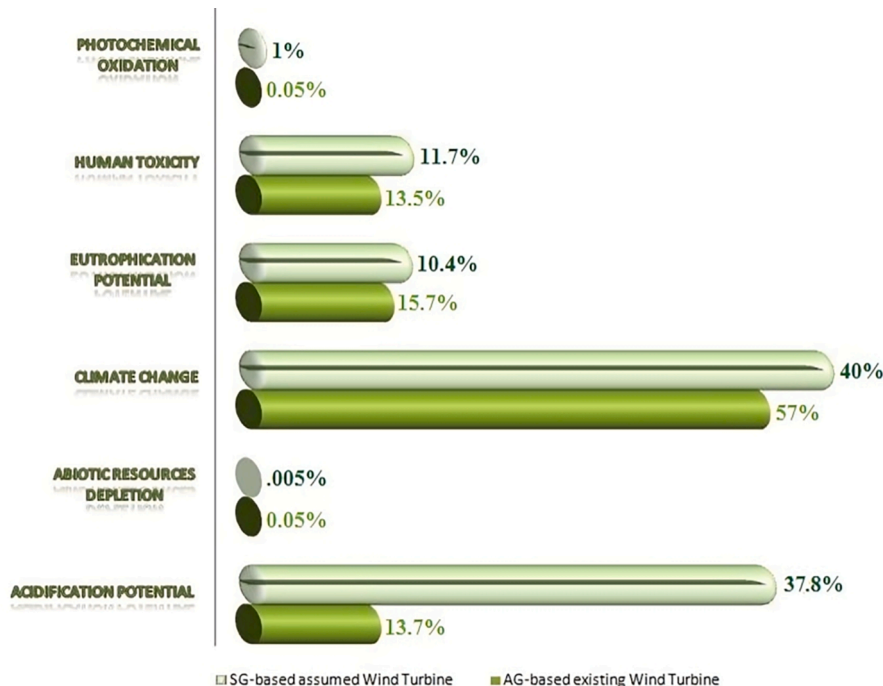


Fig. 1. Calculated Total EEEE of AG-based existing and SG-based assumed Wind Farm.

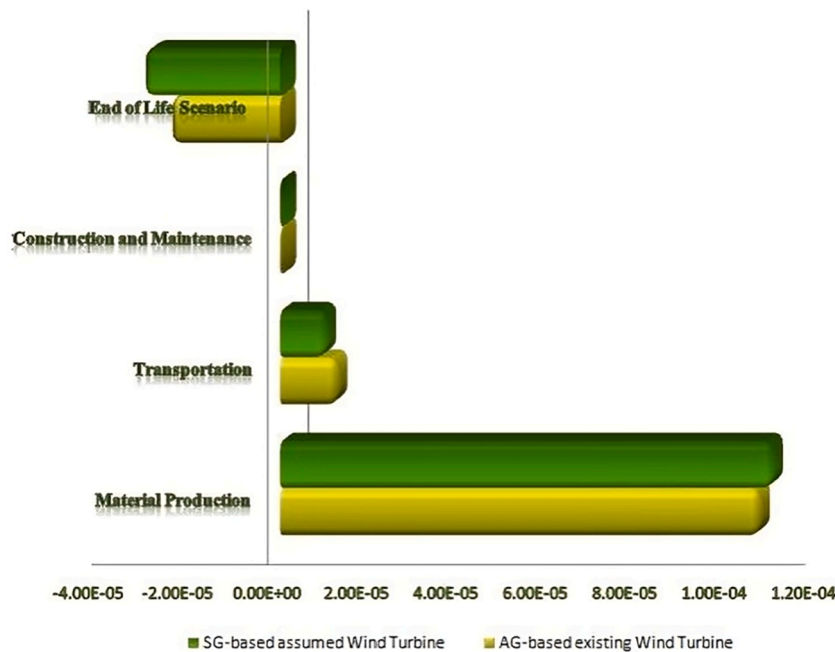


Fig. 2. Calculated EEEE from each section of AG-based existing and SG-based assumed Wind Farm for 1 kW electricity yield.

highest contribution in EEEE followed by transportation, construction and maintenance section. SG-based assumed Wind Farm contributes more than AG-based existing Wind Farm in material production section due to more number of turbines and other parts will work to generate 1 kW electricity. But in transportation section, AG-based existing Wind Farm shows more contribution as AG-based turbines have travelled higher transportation distance between the location of wind farm and the factories. In contrast, the construction and maintenance section has the lowest level of EEEE contribution for both the Wind Farms. In this case, SG-based assumed Wind Farm contributes more as the number of turbines is more and these turbines will grub more energy for construction as well as maintenance. Now, end of life section becomes negative as most of the materials used in wind farms can be recycled for reuse.

Based on LCI, the yearly environmental effective element emission rate is calculated. Fig. 3 shows the 5-yearly overall emission rate of environmental effective elements for both the Wind Farms. Basically, all the natural products are used in production of any components [44]. The EEEE rate is high in 0 year because it includes production, transportation, and construction of different items used in Wind Farms. When

the Farm starts its operation, the emission rate becomes negligible due to less emission of EEEE. This phase is started from 1st year and ends to almost 19th year if the wind farm's life is 20 years considered. After the operational phase, environmental effective element emits during the end-of-life of Wind Farm. But it is not shown in the figure as this phase of year saves more fresh use of different non-renewable materials by reusing farm's parts.

Sensitivity result in emission of environmental effective elements by considering wind speed

From the concept of working of synchronous generator and asynchronous generator in wind turbine, it is clear that asynchronous generators can generate more power run at low speed as it has a gearbox. But synchronous generator couldn't able to reach same level generation at low speed as it is directly connected to the rotor hub [38]. Therefore, asynchronous generators can give more electricity at low wind speed. For sensitivity test, working of both the chosen generators in presence of different wind speed are to be taken into mind.

To set the relationship between turbine-generator set, wind speed and environmental effective elements emission, the year to year variable wind speeds are taken into consideration. Here, three different scenarios are chosen for sensitivity analysis. As the chosen AG-based existing wind farm is started from 2012, 5-years variation data are taken into account. At the starting period of the wind farm is chosen as the first scenario, after 5 years of the wind farm is chosen as the second scenario and the present time is considered as the third scenario. Fig. 4 shows the comparative analysis of ERT by considering wind speed under three scenarios of the system. Result shows under the same wind speed in both the AG-based existing and SG-based assumed Wind Farms, SG-based assumed Wind Farms required more time for ERT operation as it needs comparatively high energy for overall sections of the life cycle and gives low output. Contrariwise, at same wind speed, the AG-based existing gives more output, so that, it's EPT become lower.

Fig. 5 shows different cases for EEEE intensity calculation by considering wind speed throughout the different life sections of the wind farms. The highlighted portion shows an effective section among the Wind Farm's life cycle. Other sections don't have any direct relation to wind speed. As the wind speed is only effective on the construction,



Fig. 3. 5-yearly overall emission rate of environmental effective elements for both the Wind Farms.

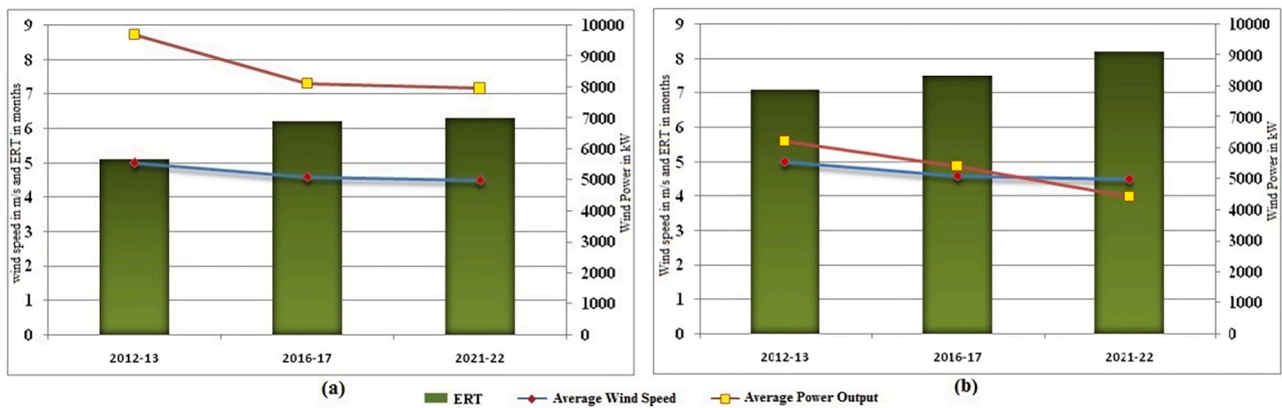


Fig. 4. Comparative analysis of ERT by considering wind speed under three different scenarios of the system. (a) is for Asynchronous turbine-generator set and (b) is for Synchronous turbine-generator set.

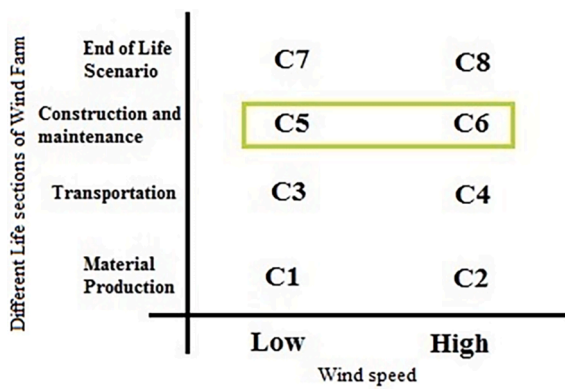


Fig. 5. Different cases for EEEE intensity for both the Wind Farms.

production, and maintenance section of the wind farm [45], Fig. 6 shows the relation of wind speed with EEEE intensity on construction and maintenance section for both the wind farms. Simply, increased wind speed will be responsible for increase in the power output of the wind farm. When more power output will generate, more maintenance will be required. More maintenance means more fuel utilization. More utilization of fuel could increase to more emission.

Conclusion

Wind energy is considered as one of the cleanest energy in the power world. But still, there is some pollutants emission present in the different life sections of the wind farm. To calculate these emission factors, LCA's environment impact analyzing methodology is used. The combination structure of the LCA with wind generators and wind speed is presented in this paper. This study has been conducted mainly to understand the environmental impact/benefit of different wind turbine-generator sets used in the wind farm. Here, construction portion of wind farm only is taken for LCA analysis. For this, one existing wind farm is taken for case study operation and one assumed wind farm is chosen from same wind class to compare the function of them. All the real-time data of existing wind farm is considered for proper justification.

In result, SG-based assumed Wind Farm showed more Environmental Effective Elements Emission as compared to AG-based existing Wind Farm due to their internal construction. Except one or two impact groups, SG-based assumed Wind Farm shows the higher impact on the every impact groups. Material production section of wind farm showed maximum Environmental Effective Elements Emission for both the wind farms; still SG-based assumed Wind Farm is on lead. SG-based assumed Wind Farm required more energy return time as it produces limited

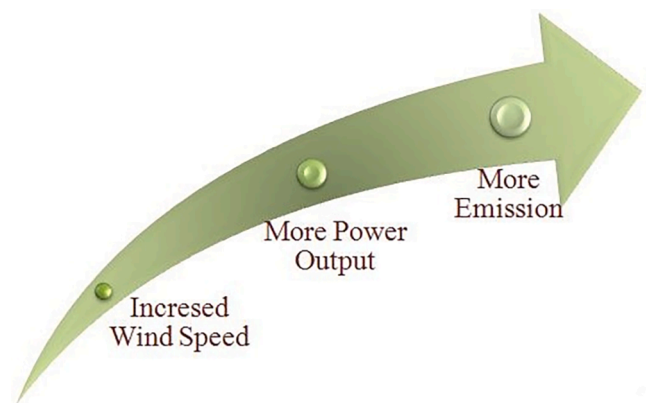


Fig. 6. Relation of wind speed with EEEE intensity on construction and maintenance section.

power output at moderate speed. Therefore, AG-based existing Wind Farm presented more suitable option for wind technologies.

Moreover, wind speed doesn't have any direct impact on LCA, but it affects the construction and maintenance phase or section of the wind farm. Increased wind speed hits the turbine blades and produces more electricity. Sometimes, speedy wind breaks the different parts of the wind farm and then extra maintenance and repairing are got added with LCA. Therefore, this increased wind speed has trends to increase Environmental Effective Elements Emission in construction and maintenance section. Furthermore, this study will help the future researcher to understand the difference in the utilization of synchronous generators and asynchronous generators in wind power production technology for a clean future of the earth.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2022.102647>.

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