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Impact of Different Parameters on Life Cycle Analysis, Embodied Energy and Environmental Emissions for Wind Turbine System

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Abstract

Due to the rapid depletion of fossil fuel reserves and increasing concern for climate change as a result of greenhouse gas effect, every country is looking for ways to develop eco-friendly renewable energy sources. Wind energy has become a good option due to its comparative economic advantages and environment friendly aspects. But there is always an ongoing debate if wind energy is as green as it seems to appear. Wind turbines once installed do not produce any greenhouse gases during operation, but it can and may produce significant emissions during manufacture, transport, installation and disposal stages. To determine the exact amount of emissions, it is necessary to consider all the stages for a wind turbine from manufacture to disposal. Life Cycle Analysis (LCA) is a technique that determines the energy consumption, emission of greenhouse gases and other environmental impacts of a product or system throughout the life cycle stages. The various approaches that have been used in the literature for the LCA of wind turbines have many discrepancies among the results, the main reason(s) being different investigators used different parameters and boundary conditions, and thus comparisons are difficult. In this paper, the influence of different parameters such as turbine size, technology (geared or gearbox less), recycling, medium of transport, different locations, orientation of the blade (horizontal or vertical), blade material, positioning of wind turbine (land, coastal or offshore), etc. on greenhouse gas emissions and embodied energy is studied using the available data from exhaustive search of lite-

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rature. This provides tools to find better solutions for power production in an environmental friendly manner by selecting a proper blade orientation technique, with suitable blade material, technology, recycling techniques and suitable location.

Keywords

Embodied Energy, Energy Payback Time, Emissions, Life Cycle Analysis, Wind Energy

1. Introduction

The increasing demand for energy in the world is not only threatening our environment due to the pollutant emissions from the combustion of fossil fuels (natural gas, oil and coal) but also causing concern for future of energy once we deplete these resources. World population in 2015 is 7.3 billion and expected to rise to 8.4 billion by 2030. The major source of energy in almost all of the countries is still fossil fuel. However, the present reserves of fossil fuel resources cannot be expected to last forever. The total Greenhouse Gas (GHG) emissions globally in 2010 were 54 Gt CO_2e [1] and are projected to be 70 Gt CO_2e in 2050 [2]. This is a serious concern for the future generations. For the above mentioned and other reasons, the use of renewable energy sources is steadily increasing across the globe. Among the various sources of renewable energy, wind, solar, biofuels, and hydroelectricity are the most significant ones. There has been a sharp increase in the installation of wind turbines for energy production in the past few years. For example, just in the U.S. there are plans to produce 20% of the energy needs from wind by the year 2030 [3]. The biogas, hydroelectricity and nuclear energy are also very reliable and environmentally friendly. But there are associated limitations with all the options, such as the extremely radioactive, spent fuel from nuclear energy, or the processes involved with biogas and hydroelectricity and the comparative outcome of all the sources. So the fact that wind energy does not use fossil fuel is not enough to claim that it is the best replacement for fossil fuel and a better solution for the environment. Life cycle analysis helps to estimate the actual amount of GHG emissions, Energy Payback Time (EPBT) and compare those with other renewable and other energy sources.

Life Cycle Analysis (LCA) is a technique used to determine the energy consumption (Embodied Energy), GHG emissions and environmental impacts of a product or system throughout the life cycle stages (cradle to grave) namely, extraction of raw materials, transportation, manufacture, installation and disposal with or without recycling [4]. Through the life cycle analysis, it is possible to determine the environmental impact of a product or a process. Generally, LCA consists of various steps. At first, the goal and the scope of the LCA are fixed. A reference unit is included-all input and outputs are related to this reference. This reference unit is called the functional unit, which provides a clear, full and definitive description of the product or the service being investigated, enabling subsequent results to be interpreted correctly. The second step is called Life Cycle Inventory (LCI), where the process is considered as a sequence of subsystems that exchange inputs and outputs. In LCI, the product system is defined by setting the system boundaries, designing the flow diagrams with unit processes, and collecting the data for each of the processes in which emissions will occur. The subsequent step is the impact assessment. This includes the impacts of a product or process in terms of emissions and raw material depletions. Lastly, a comparison with other processes offering a similar utility and a critical view of these previous steps are done. This is referred to as the interpretation step.

Various studies have been done on the LCA of wind turbine considering various parameters. The effects of wind turbine size on embodied energy and GHG emissions were studied by different researchers [5]-[8]. Influences of different technologies were considered the main focus point in some studies [9]. The effects of recycling of materials, different location of the wind turbine and transport were considered in some LCA studies [6] [7] [9]-[13]. The effects of blade orientation, blade material and wind turbine positioning were also studied through LCA [12] [14]-[19].

In the literature, different researchers used different parameters, approaches and boundary conditions for the life cycle analysis of wind turbine making it difficult to compare. The main purpose of this paper is to determine the effect of different parameters such as selection of turbine size, technology (geared or gearbox less), recycling, medium of transport, the location of the wind farm, the orientation of the blade (horizontal or vertical), blade material and wind turbine positioning on LCA and embodied energy and GHG emissions.

2. Methodology

The main purpose of this paper is to study the effect of different parameters chosen by different researchers for life cycle analysis in order to investigate the effects of those parameter on life cycle analysis, embodied energy and energy emission. It has been observed that for performing life cycle analysis, different researchers have focus on different parameters. Some have compared the embodied energy and environmental emission for increasing turbine size [5]-[8], some have given emphasis on different technology [9], some have considered effect of recycling [9]-[12], some have given attention on location, transport, blade orientation, blade material and blade positioning [9] [12]-[16]. The aim of the paper is to investigate all this parameters on LCA, embodied energy and emissions. So that, in case of establishing a wind turbine one can consider all these parameter and by choosing proper size, proper location, blade orientation, blade material, recycling method can establish a more energy efficient and environment friendly way. For attaining this purpose, in this paper a certain numbers of research works have been chosen and carefully studied. It is difficult to make comparison because the parameters are different. However, at least it will give an idea of the impact of those parameters. For making the comparison easier, it has been tried to bring the embodied energy, energy output and environmental emission of all researcher's data to same unit. The embodied energy is converted to kJ/kWh, the energy output is MWh/yr and environmental emission is to g CO_2e/kWh.

3. The Factors Influencing Life Cycle Analysis, Embodied Energy and Environmental Emissions

As noted earlier, various studies in the literature used various approaches, boundary conditions, life cycle assessment stages and different parameters for the LCA. Thus, there are significant differences in energy embodied in the production, the EPBT and GHG emissions. The various parameters that influence the LCA, energy embodied in the product or system and GHG emissions are discussed in the following sections.

3.1. Impact of Turbine Size

Due to the greater output and increasing efficiencies, there is an increasing trend towards larger wind turbine size (1 MW and above). As can be expected, with the increase in the size of the wind turbine, not only the output increases, but also the required material and embodied energy for manufacturing increases. However, it is necessary to determine whether these increases in wind turbine size and embodied energy provide a net energy saving and lower environmental impact.

The dimensional effects of wind turbines have been studied through LCA by different researchers [5]-[8]. Though the main target in each of these LCA was to find the effect of wind turbine size on embodied energy, net energy output and greenhouse gas emissions, the assumptions and methodologies of each of the researchers were different. Crawford [5] reported the life cycle analysis of wind turbine of two sizes, 850 kW and 3.0 MW, using hybrid embodied energy analysis approach. A 3-bladed horizontal axis wind turbine with an anticipated lifetime of 20 years is selected. While, Tremeac and Meunier [6] chose 4.5 MW and 250 W wind turbine for making comparisons, a different approach was used by Kabir *et al*. [7] where they considered three configurations of wind turbines to produce the same name plate power of 100 kW: twenty Endurance 5 kW, five Jacobs 20 kW and one northern Power 100 kW. Demir and Taskin [8] compared the energy output and environmental effects of three medium scale wind turbines (330, 500, 810 kW) and two large scale wind turbines (2050 and 3020 kW) at three different hub heights (50, 80, 100 m). **Table 1** shows the summary of the embodied energy (energy consumed) per kWh of energy output, energy output and the environmental effect for different sizes of wind turbines along with the sources of the data.

Though different researchers considered different situations, a common result is observed from the life cycle analysis of different sizes of wind turbines that though the embodied energy for large size wind turbines is higher, the net output as expected is higher. As a result, embodied energy per kWh output is lower for large wind turbine. Moreover, the large wind turbines have a greater positive environmental effect compared to smaller wind turbines. In the LCA of Crawford [5], it is observed that for 850 kW wind turbine the annual output is 9486 MWh and the environmental emission is 9.29 g CO_2e/kWh. However, for 3 MW wind turbine annual output have increased to 32,915 MWh and the environmental emission is decreased to 8.40 g CO_2e/kWh. A similar trend is observed in LCA by Tremeac and Meunier [6] between a 4.5 MW and a 250 W wind turbine. It becomes

Table 1. Embodied energy, energy output and environmental emission for different sizes of wind turbine.

Parameters	Quantity	Embodied energy (kJ/kWh)	Energy output (MWh/yr)	Environmental impact (g CO_2e/kWh)	Source
850 kW	1	154.90	9486	9.29	Crawford [5]
3.0 MW	1	140	32,915	8.40	
4.5 MW	1	300	11,700	15.80	Tremeac and Meunier [6]
250 W	1	1200	2.00	46.40	
5 kW	20	424.3	204	17.80 net avoided	Kabir *et al*. [7]
20 kW	5	221.5	196	25.10 net avoided	
100 kW	1	133.3	212	42.70 net avoided	
330 kW (100 hub height)	1	-	746	33.9633	Demir and Taskin [8]
500 kW (100 hub height)	1	-	1010	29.97	
810 kW (100 hub height)	1	-	1670	20.41	
2050 kW (100 hub height)	1	-	3960	16.27	
3020 kW (100 hub height)	1	-	3990	22.29	

more evident from the LCA results of Kabir *et al*. [7], it shows that for the same name plate output power of 100 kW, the embodied energy per kWh of output is lower and net avoided environmental emission per kWh of output is higher for a single 100 kW wind turbine than the combinations of same name plate power using different smaller turbines. A single 100 kW wind turbine needs 133.3 kJ/kWh embodied energy which is less than the embodied energy needed for 5 numbers of 20 kW (5 - 20 kW) wind turbines (221.5 kJ/kWh) and 20 numbers of 5 kW (20 - 5 kW) wind turbines (424.3 kJ/kWh). It should also be noted that 5 - 20 kW units are more efficient than 20 - 5 kW units. The energy output for the 3 configurations is in the range of 196 - 212 MWh/yr. The net avoided emissions from single 100 kW wind turbine are 42.7 g CO_2e/kWh and gotten lower (25.1 g CO_2e for 5 - 20 kW and 17.8 g CO_2e for 20 - 5 kW) as the size decreased. The net avoided emissions for single 100 kW wind turbine are almost three times and two times higher than the 20 - 5 kW or 5 - 20 kW wind turbine configurations respectively. Along with the sizes of the wind turbine, Demir and Taskin [8] also considered different hub heights. In this paper, only the 100 m hub height systems are used for analysis. As can be seen from the analysis, the large turbines give better energy efficiency and lower environmental impacts than the medium or small wind turbine units, but increasing the size after a certain range may increase environmental emission. It is noted from the data of Demir and Taskin [8], the increase in size from 2050 kW to 3020 kW increased the g CO_2e/kWh emission after steady decrease emission when we increased the size from 330 kW to 2050 kW. The 2050 kW wind turbine gives almost the same output but with lower environmental emission than the 3020 kW unit.

3.2. Impact of Technology

In order to determine the effect of using different technologies such as gearbox on material usage, CO_2 emission and EPBT, Guezuraga *et al*. [9] performed LCA of two turbines: 1.8 MW gearless turbine and 2.0 MW turbine with a gearbox. For LCA, the entire life cycle from manufacture of components to decommissioning were considered. The manufacturing part includes mining, refining, processing and construction of the main components like the rotor, nacelle, tower and foundation. Again, the effect of transportation, operation and maintenance, dismantling and recycling were also considered.

The total cumulative energy requirements, annual energy generated, EPBT and environmental emissions expressed as CO_2e emissions for the 2.0 MW geared turbine and 1.8 MW gearless turbine are calculated. It is observed that the 2.0 MW geared turbine required little more energy (117.69 kJ/kWh) than the 1.8 MW wind turbine (116.15 kJ/kWh). But the 2.0 MW geared turbine generated 5980 MWh annually, while the 1.8 MW gearless turbine generated 3270 MWh only. The EPBT are 0.65 yr and 0.64 yr for the 2 MW geared turbine and 1.8 MW gearless turbine respectively. However, the 1.8 MW gearless wind turbine has a better environmental value than the 2.0 MW geared turbine in terms of the CO_2 emission. The gCO_2e/kWh for 2.0 MW geared turbine is

9.73 which is slightly higher than the emissions from the 1.8 MW gearless wind turbine (8.82 g CO_2e/kWh). So it is observed that using a gear box increases the output, however, it also increases the energy required and the GHG emissions (**Table 2**).

Table 2. Embodied energy, energy output and environmental emissions for geared 2.0 MW and gearless 1.8 MW turbines.

Parameters	Embodied energy (kJ/kWh)	Energy output (MWh/yr)	EPBT yr	Environmental impact (g CO_2e/kWh)	Source
2.0 MW-geared	117.69	5980	0.65	9.73	Guezuraga *et al.* [9]
1.8 MW-gearless	116.15	3270	0.64	8.82	

3.3. Impact of Recycling of Wind Turbine Material

The recycling of wind turbine materials has a great impact on LCA, required embodied energy, annual output and environmental emissions. The effect of recycling has been studied using LCA by different researchers [9]-[12]. Martinez *et al.* [10] studied the LCA of multi megawatt wind turbines. One of the purposes of the study was to analyze the part by part recycling effects of the wind turbine. It is observed that the parts whose recycling gives the highest level of environmental favors is the tower, nacelle, rotor and foundation. It can be noted from **Table 3** that by recycling foundation with nacelle for the 2 MW wind turbine, the net avoided Global Warming Potential (GWP) increased from 2356 pt to 2615 pt. The following year, the authors [11] conducted a sensitivity test of the earlier LCA considering four scenarios. One of the scenarios was to study the environmental impact using a 50% reduction of the recycling. It can be observed from **Table 3**, that the environmental emissions increased by 11,500 pt. Guezuraga *et al.* [9] completed the LCA of the previously mentioned 2 MW geared turbine considering the recycling of materials. Recycling of stainless steel, cast iron and copper is considered, whereas epoxy, plastic, fiberglass and concrete production are considered to be derived from crude oil or minerals.

Table 3. Embodied energy, energy output and environmental impact for recycling of material.

Specifications	Scenarios	Embodied energy (kJ/kWh)	Energy output (MWh/yr)	EPBT yr	Environmental impact	Source
2 MW wind turbine	Nacelle, rotor, tower	-	4000	0.40	2356 pt GWP avoided	Martinez *et al.* [10]
	Nacelle, rotor, tower, foundation	-	4000	0.40	2615 pt GWP avoided	
2 MW wind turbine	Reduction by half of the recycling	-	-	-	Approximate. 11, 500 point increase	Martinez *et al.* [11]
2 MW geared turbine	BCRS	-	-	0.69	9.78 g CO_2e/kWh	Guezuraga *et al.* [9]
	WCRS	207.99	5980 (2990 h)	1.15	17.35 g CO_2e/kWh	
	WCRS and WCOS	358.44	3470 (1738 h)	1.99	29.48 g CO_2e/kWh	
Vertical axis	100% reuse	0.00927	0.539	-	6.3079 g CO_2e/kWh	Uddin and Kumar [12]
	90% reuse	0.01763			5.7514 g CO_2e/kWh	
	80% reuse	0.02597			5.1948 g CO_2e/kWh	
Horizontal axis	100% reuse	0.002245	1.782	-	1.7677 g CO_2e/kWh (avoided)	
	90% reuse	0.0030864			1.6554 g CO_2e/kWh (avoided)	
	80% reuse	0.0035476			1.54320 g CO_2e/kWh (avoided)	

The result obtained from the Best Case Recycling Scenario (BCRS) is compared with the Worst Case Recycling Scenario *i.e*. without recycling (WCRS) and Worst Case Operation Scenario (WCOS) in terms of embodied energy required, annual energy generated, EPBT and environmental emissions. The results obtained are included in **Table 3**. It is observed that with WCRS, the g CO_2/kWh increased from 9.78 to 17.35 and the EPBT increased from 0.65 to 1.15 years. Again, comparing the WCRS and WCOS with 30% grid curtailment and 2% degradation factor, the new EPBT increased to 1.99 years and emissions are 29.48 g CO_2/kWh. Uddin and Kumar [12] performed a comparative LCA of the horizontal axis and vertical axis wind turbines and included the effect of recycling. It is observed that in case of 100% reuse of the material, the vertical axis wind turbine requires less energy and 6.3079 g CO_2e/kWh of emissions can be avoided compared to 5.7514 g CO_2e/kWh and 5.1948 g CO_2e/kWh of emissions for 90% and 80% of recycling respectively. A similar trend is observed for the horizontal axis wind turbine for energy requirement and environmental emissions. The 100% reuse of material requires less energy and the largest amount of environmental emissions can be avoided.

3.4. Impact of Geographic Location of Wind Turbine

One of the important parameters affecting the LCA is the geographic location of the wind turbine farm, specifically the country. In order to determine the effect of location on the LCA, energy required, annual energy output and environmental emissions (g CO_2e/kWh), Guezuraga *et al*. [9] conducted LCA of the previously mentioned 2 MW geared turbine in perspective of three different countries, China, Denmark and Germany-all of which have different mixes of energy. Germany and Denmark have facilities to manufacture the different components, where China has relatively low labor cost. The final product is the same whether produced in China or in Denmark. The emissions to produce the exact same product will vary depending on the mix of energy used to produce electricity in each country. **Table 4** shows the new results depending on the various locations. It is observed that when the same 2 MW geared turbine is produced in China, the energy requirement increases to 424.41 kJ/kWh, while the energy requirements are 207.69 kJ/kWh and 242.61 kJ/kWh respectively in Germany and Denmark. The energy payback time in China (38.33 yr) is also higher than the energy payback time for Germany (17.35 yr) and Denmark (23.26 yr). The emissions increased to 38.33 g CO_2e/kWh in case of production in China, while the emissions are the lowest (17.35 g CO_2e/kWh) when turbine is produced in Germany. A similar analysis was done by Lenzen and Wachsmann [13] for the energy requirement, energy generated and environmental emissions of a single product using different locations. Five scenarios were considered for the case study to prove that the background system and the economy of the location of the product demonstrate the variability in energy input and CO_2 emissions. Two countries are considered-Germany and Brazil where oil based fuel consumption is high in both countries. However, natural gas and nuclear energy are only important for German industries and hydraulic energy, bagasse, firewood and sugar-cane-based alcohol are a unique feature of Brazil. More renewable energy is available in Brazil and as the conversion efficiency of hydraulic energy

Table 4. Results for different manufacturing locations for 2 MW-geared turbine.

Specifications	Locations	Embodied energy (kJ/kWh)	Energy output (MWh/yr)	EPBT yr	Environmental impact (g CO_2e/kWh)	Sources
2 MW geared turbine	Germany	207.69	5980	1.15	17.35	Guezuraga *et al.* [9]
	Denmark	242.61	5980	1.35	23.26	
	China	424.41	5980	2.36	38.33	
E-40 turbine (inland 65 m height)	P&O in Germany	730	881.972	-	7.7×10^{-5}	Lenzen and Wachsmann [13]
	P in Germany, O in Brazil	290	2420.131	-	2.6×10^{-5}	
	P Germany & Brazil, O Brazil	220	2420.131	-	1.2×10^{-5}	
	P&O in Brazil	190	2420.131	-	4×10^{-6}	
	P&O in Brazil, recycled steel	140	2420.131	-	3×10^{-6}	

P = Production, O = Operated.

is much higher than that of coal, when the wind turbine is produced and operated (P&O) in Brazil, it shows the least energy requirement (140 kJ/kWh) and least CO_2 emissions (3×10^{-6} g CO_2e/kWh).The wind turbine produced and operated in Germany required the highest energy (730 kJ/kWh) and the highest CO_2 emission (7.7×10^{-5} g CO_2e/kWh).

3.5. Impact of Transportation

In order to determine the effect of transportation on life cycle analysis, Tremeac and Meunier [6] did a sensibility test changing distance and medium of transport. For a 4.5 MW and 250 W wind turbines, they considered two cases. In one case (case A) distance increased twice more than the reference case and in the other case (case B) transport medium is considered as train instead of truck. Only one case was considered at a time. **Table 5** shows the results. It is observed that type and transport distance is an important factor for human health, resources and climate change. It is observed that as a result of increasing the distance, the embodied energy required, CO_2 emissions and human health factor increase 360 kJ/kWh primary non-renewable energy, 21.20 g CO_2/kWh and 7.375DALY respectively. For the same scenario when the medium of transport changed from train to truck, the embodied energy required, CO_2 emissions and human health factor changed to 252 kJ/kWh primary non-renewable energy, 12.10 g CO_2/kWh and 3.347 DALY respectively. Similar trend is observed for 250 W wind turbine.

Table 5. Influence of the transport in the life cycle assessment of the 4.5 MW and 250 W wind turbine.

Specifications	Impact category	Embodied energy (kJ/kWh)	Climate change (tgCO_2e)	Environmental impact (g CO_2e/kWh)	Human health (DALY)	PEPBT yr	Source
4.5 MW wind turbine	Reference	288	3691.1	15.80	5.126	0.58	Tremeac and Meunier [6]
	Case A (distance variation)	360	4956.5	21.20	7.375	0.72	
	Case B (type of transport variation)	252	2835.5	12.10	3.347	0.51	
250 W	Reference	1138	115.5	46.40	4×10^{-4}	-	
	Case A (distance variation)	1332	141.2	58.80	4.30×10^{-4}	-	
	Case B (type of transport variation)	1044	85.8	35.80	3.80×10^{-4}	-	

3.6. Impact of Blade Orientation (Horizontal Axis and Vertical Axis Wind Turbine)

It has been observed that most of the life cycle analysis of the wind turbine is done on the horizontal axis wind turbine as it is the most commonly used turbine. Due to many structural and manufacturing advantages, the horizontal axis wind turbine is becoming more popular. In 2014, Uddin and Kumar [12] made a comparative life cycle analysis of the vertical axis wind turbine and horizontal axis wind turbine. The vertical axis wind turbine is comprised of a turbine, rotor, three frames, tower, generator, switchboard and inverter. For the vertical axis wind turbine, the fan was made of aluminum and the rotor was made of galvanized steel. The horizontal axis wind turbine is comprised of blades, nacelle, a tail rod, switch board and inverter. The turbine blades of the horizontal axis were made of fiberglass plastic. A thorough life cycle analysis was done considering extraction of raw materials, transportation, and manufacture of component parts, distribution, installation, use and disposal.

Table 6 shows the embodied energy, energy output and the emissions and environmental impacts of the horizontal axis wind turbine and vertical axis wind turbine. It is observed that the required embodied energy of the vertical axis wind turbine is 19,382 kJ/kWh which is higher than that of the horizontal axis wind turbine

(18,280.8 kJ/kWh). The electricity generated from the horizontal axis wind turbine and vertical axis wind turbine was studied for over a year. The load factor was considered 35%. It was observed that the energy output of the vertical axis wind turbine is 0.539 MWh/yr and the horizontal axis wind turbine is more than double of that (1.782 MWh/yr). The total emissions and environmental impacts of both the wind turbines were also studied in terms of CO_2, SO_4 and GWP. It is observed that CO_2 and SO_4 emissions per functional unit are 0.24 kg and 9.55 gm respectively for the vertical axis wind turbine and 0.08 kg and 3.39 gm respectively for the horizontal axis wind turbine. The GWP is also larger for the vertical axis wind turbine. So considering all the aspects-total energy embodied, energy production and emission etc., it can be decided through the life cycle analysis that the horizontal axis wind turbine provides a far better overall result.

Table 6. Life cycle embodied energy, energy output and the total emissions and environmental impacts of horizontal axis wind turbine and vertical axis wind turbine.

Parameter	Embodied energy (kJ/kWh)	Energy output (MWh/yr)	CO_2 Kg	SO_4 gm	Environmental impact (g CO_2e/kWh)	Source
Vertical axis wind turbine	19382	0.539	0.24	9.55	5400	Uddin and Kumar [12]
Horizontal axis wind turbine	18280.8	1.782	0.08	3.39	1800	

3.7. Impact of Blade Material

The selection of blade material is an important parameter which can influence energy embodied and greenhouse gas emissions. From the comparison between the horizontal and vertical axis wind turbine discussed in the earlier section, it is observed that the embodied energy and emissions are high for a vertical axis wind turbine. Uddin and Kumar [12] further showed that by changing the blade material of the vertical axis wind turbine, the embodied energy and emissions could be decreased. Previously the blade was made of aluminum. Uddin and Kumar replaced aluminum at first by thermoplastic and then by fiberglass plastic. The change in result of embodied energy and environmental emissions are shown in **Table 7**. It is observed that the required embodied energy has decreased drastically from 50 kJ/kWh to 30 kJ/kWh and 25 kJ/kWh for thermoplastic and fiberglass plastic respectively. The change of environmental emissions from the three materials are also observed. It is observed that due to the use of thermoplastic fan and fiberglass fan, the amount of CO_2 emission decreased from 12 g CO_2e/kWh to 10.5 g CO_2e/kWh and 10 g CO_2e/kWh for thermoplastic and fiberglass plastic respectively. For SO_4 emissions, no significant change is observed.

So it can be concluded that the blade material can provide a much improved embodied energy and environmental emissions by utilizing newer composites as opposed to aluminum.

Table 7. Emissions and environmental impact of vertical axis wind turbine for alternative materials.

	Embodied energy (kJ/kWh)	Energy output (MWh/yr)	Environmental impact (g CO_2e/kWh)	Source
Aluminum fan (Base case)	50	0.539	12	Uddin and Kumar [12]
Thermoplastic fan	30	0.539	10.5	
Fiberglass plastic fan	25	0.539	10	

3.8. Impact of Wind Turbine Placement (On-Land, Coastal or Offshore)

The position of the wind turbine, whether on-land, coastal or offshore area, has a significant impact on the environment and energy production. The wind turbines on coastal and offshore area generally get higher wind velocity as compared to the ones on the land. So the energy output is higher for them. But the offshore and the coastal wind turbine require special support due to the tides. This may cause higher cost and larger environmental effects.

Various researchers considered the position of the wind turbine as an important parameter in their life cycle analysis [14]-[16]. Angelakoglou *et al*. [14] in 2013 performed life cycle analysis of three wind turbines, with a power rating of 3000 kW each, considering three positions—land, coastal and offshore. He showed that the total environmental effect of the land, coastal and offshore wind turbine are 195,000 pt, 301,000 pt and 452,000 pt respectively. Schleisner [15] performed a life cycle assessment for an offshore wind farm and an onshore wind farm of 5 MW and 9 MW capacity respectively. He also gets similar environmental effects. Wang and Sun [16] did their research on life cycle analysis on the wind turbine farm considering three wind farms in three developed countries, one of them is offshore, and compared the result with an onshore wind farm in China. In this case also, it is observed that though the energy output of the offshore wind turbine is highest (1423×10^3 MWh/year), the environmental effect of the offshore wind turbine is comparatively higher than the onshore wind turbine (5.98 gm CO_2e/kWh). **Table 8** shows the results of these studies. It is observed that in all three cases the land wind turbine shows more environmentally friendly results. But the offshore wind turbines exhibit better performance in terms of energy and financial issues compared with the offshore and coastal turbines. Even though its initial investment cost is higher, the initial investment cost is compensated by its superior financial performance.

Table 8. Energy, financial estimation and environmental effect of 3 MW Vest as V90 wind turbine versions.

Specifications	Locations	Embodied energy (kJ/kWh)	Renewable energy	Environmental impact	Source
3000 kW wind turbine	Land (85 m)	-	5001/yr	195,000 pt	Angelakoglou *et al.* [14]
	Coastal (95 m)	-	10,989/yr	301,000 pt	
	Offshore (105 m)	-	15,519/yr	452,000 pt	
5 MW wind farm	Offshore	175.49	12,500 MWh/yr	16.5 g CO_2e/kWh	Schleisner [15]
9 MW wind farm	Onshore	118.08	19,800 MWh/yr	9.7 g CO_2e/kWh	
186 × 1.65 MW	Onshore	-	1073×10^3 MWh/year	8.21 g CO_2e/kWh	Wang and Sun [16]
100 × 3 MW	Offshore		1423×10^3 MWh/year	5.98 g CO_2e/kWh	
100 × 3 MW	Onshore		789×10^3 MWh/year	4.97 g CO_2e/kWh	
116 × 850 kW	Onshore		198×10^3 MWh/year	0.19 - 0.28 g CO_2e/kWh	

4. Conclusions

The purpose of this research was to study the various parameters that influence the life cycle analysis of the wind turbine. It has been observed from the previous results that there are significant differences that arise among the results of life cycle analysis, required embodied energy and environmental emissions due to selecting different parameters and different analysis techniques. It is observed that a significant change of energy embodied, energy generated and greenhouse gas emissions is observed due to change of the analysis process, turbine size, technology (geared or gearbox less), recycling, medium of transport, different location, orientation of the blade (horizontal or vertical), blade material and positioning of the wind turbine. These parameters can be very helpful in making decisions for better power production and better environmental effects.

From the life cycle analysis, it can be concluded that the large scale wind turbines are more energy efficient and more environmentally friendly than the medium scale wind turbine. However, wind turbines that are too large in size may cause an increase in environmental emissions in the manufacturing stage. Again, using different technology such as the geared turbine increases the energy output, but also causes environmental emissions. Recycling of turbine material is a good option to decrease the initial energy requirement and environmental emissions. It is observed that when recycling different parts of the wind turbine and foundation, a better environmental effect is observed. The location (country) of wind turbines also influences the environmental emissions during the manufacturing and disposal stages as the economy of a country determines the preliminary stage energy requirements. It is observed that by choosing a location which is near to the manufacturing spot and is reachable by river, train or such medium of transport, energy requirement and environmental emissions can be decreased. The energy output and environmental effects can be improved by the choosing proper blade orientation for the wind turbine. The horizontal axis wind turbine gives better energy output and reduced GWP. Lastly, it is observed that the offshore and coastal wind turbines have greater energy output compared to an onshore wind turbine. However, offshore and coastal wind turbines need extra support and additional structural features which will increase the initial cost and environmental emissions.

The results from this life cycle analysis can be used in choosing proper turbine size, technology, recycling technique, transportation medium, suitable location and blade material, more energy efficient and environment friendly designs can be selected.

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