The Carbon Emissions of Wind Power; A Study of Emissions of Windmill in the Panhandle of Texas

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Abstract

The National Oceanic and Atmospheric Administration in its 2018 Report on "Climate Change: Current and Projected Impacts on the U.S." called for the need for removal of existing carbon from the atmosphere to prevent the projected climate disasters by 2050 (NOAA, Fahey, SOLAR 2018 Conference). This warning necessitates an examination of the carbon footprint of renewables, especially solar photovoltaic and wind generation. The electricity generation from both wind and solar photovoltaics has been on the rise globally in recent years. In this paper we study the carbon footprint of wind generation from a 1.3 megawatts (MW) located in the wind sweet spot of the U.S., namely, Panhandle of Texas. We are also investigating the carbon footprint of solar photovoltaics and will report the results in the near future.

Our model includes the carbon cost of manufacturing, transportation, installation, operation, and maintenance of windmills. Our results show that a 1.3 MW windmill operating in the Panhandle of Texas produces 14.45 grams of carbon dioxide for each kilowatt (kWh) of generated electricity. Compared to carbon dioxide intensity of 792 grams CO_2 /kWh of electricity produced by an average coal power plant, wind power generation produces 1.8% emissions, a substantial 98.2% reduction in emissions. However, with 286.8 billion kWh wind generation in 2019, this amount to 4.13 million ton (MT) of annual emissions by wind, which will increase substantially as deeper levels of wind generation is achieved in the next several decades. Our results agree well with those reported by others.

Keywords: *Wind Power Generation, Carbon Footprint of Wind, Wind Power in Panhandle of Texas*

1. Introduction

The wind power in the United States has been expanding rapidly over the last several years. For the twelve months ending September 2019, the United States generated 286.6 terawatt-hour of wind power, roughly 7% of all generated electricity (Wind Power Monthly, 2020A). A similar trend is seen in China (GWEC, 2019) and Europe (Wind Power Monthly, 2020B) which is expected to continue over the next several decades. More specifically, as shown in Fig.1, the total installed wind capacity in the U.S. at the end of first quarter of 2020 was 107,319 MW (U.S. EERE, 2020). Just in the first quarter of 2020, the wind industry installed 1,821 MW of new wind power capacity, which is a 117% increase over the first quarter of 2019. Obviously, the continued increase in wind capacity is a major step toward reducing carbon emissions. However, there are two reports that should be considered as strong warnings on the global emissions and climate change. One is the report by U.S. EIA (2020) in which it was reported that the U.S. total emissions, after ten years of decline (from 2007 to 2017) went up by about 2.5% in 2018 (See Fig. 2).

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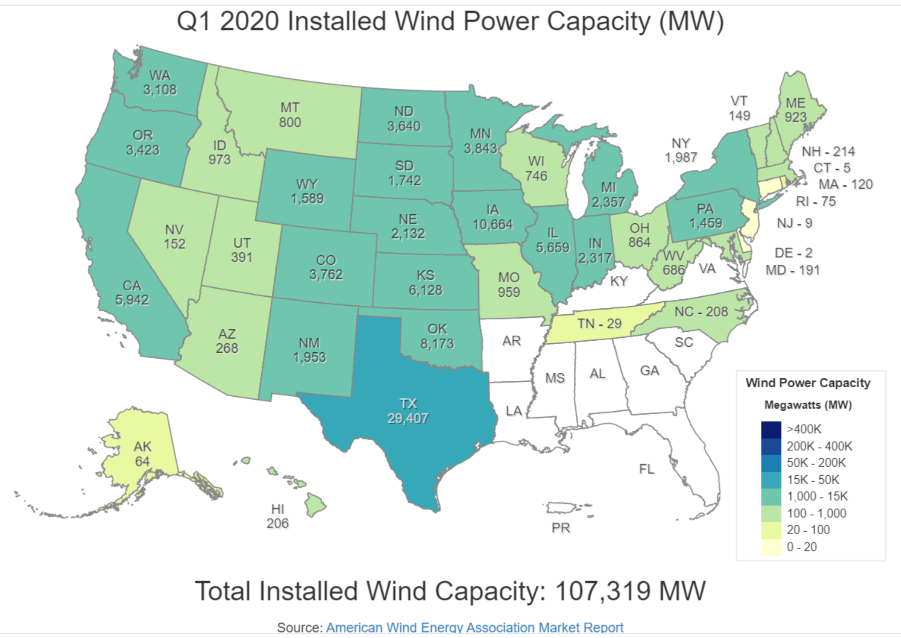
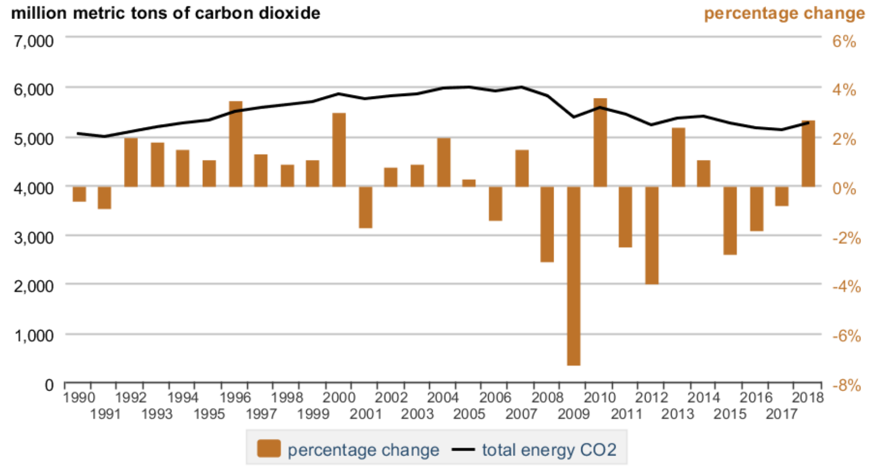


Source: American Wind Energy Association Market Report

Fig. 1. U.S. Installed Wind Power Capacity in 2020 (U.S. EERE, 2020)

We have studied the effects of recent coal deregulations on the emissions of seven eastern states in the U.S. and projected an even faster rate of increase in emissions in the next several years (Khoie and Calderon, 2020).



Source: U.S. Energy Information Administration, *Monthly Energy Review*, October 2019, Table 11.1, Carbon Dioxi

Fig. 2. Total and percentage of change in the U.S. energy-related carbon dioxide emissions. (U.S. EIA, 2020)

The second report is the National Oceanic and Atmospheric Administration 2018 Report on "Climate Change: Current and Projected Impacts on the U.S." in which it was concluded that the time has reached for the need for removal of existing carbon from the atmosphere if we are to slow down the catastrophic consequences of continued rise in total global emissions and prevent the projected climate disasters by 2050 (NOAA Fahey, 2018). As such, there is no longer a debate that electricity generation from coal and other fossil fuels must be stopped immediately. There is also no doubt that our electricity generation should become 100% renewable as soon as possible (Khoie, et. al., 2019). The warning by the National Oceanic and Atmospheric Administration necessitates a careful study of the carbon-neutrality of renewable generation in the U.S. and across the globe. This paper aims to analyze the carbon footprint (or carbon cost, or emissions intensity which is defined as CO_2 produced per kWh of electricity generated), and in particular, the emissions intensity of a 1.3 megawatts (MW) wind power located in the wind sweet spot of the U.S., namely, Panhandle of Texas.

2. Life Cycle Assessment

A number of researchers have developed models for Life Cycle Assessment of wind turbines mostly following International Organization for Standardization ISO Standard 14040 (ISO, 2006) by which the turbine is analyzed from cradle-to-grave including steps such as manufacturing, commissioning, operation, and retirement (Wind Energy, 2020), as shown in Fig. 3.

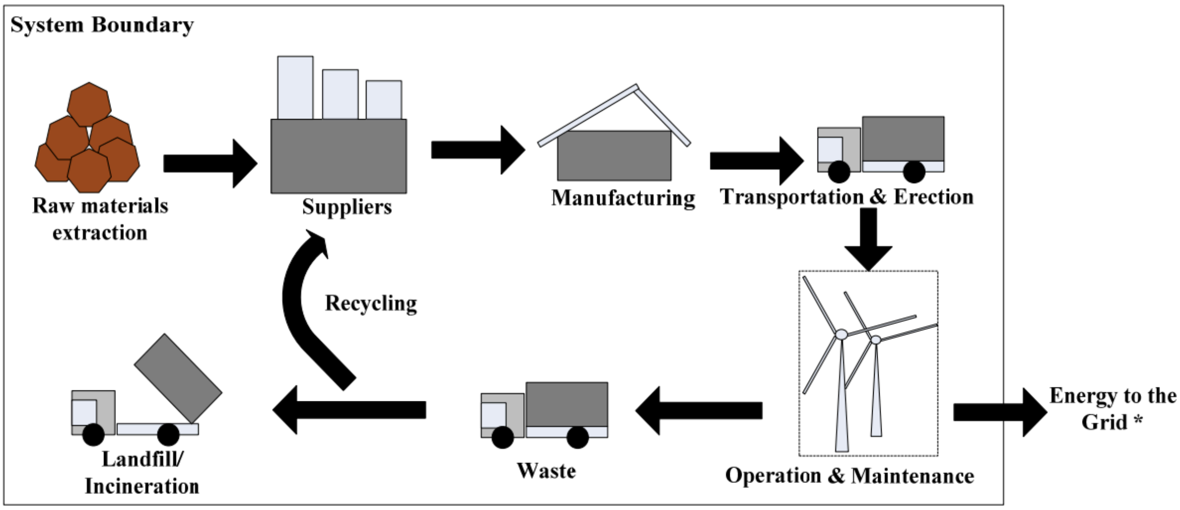


Fig. 3. Cradle-to-grave process in life cycle assessment of wind power generation (Garabedian, 2020).

Two distinct methods are generally used to quantify the carbon emissions produced throughout the lifespan of a turbine. The first method which is most commonly used is process-analysis (PA) which calculates the emissions based on the mass of the actual materials used in production. This method is a bottom-up approach that calculates the energy used in the materials in construction of a wind turbine including energy used in processes such as manufacturing, material handling, and transportation. This method focuses only on analyzing materials that are used in substantial quantities, thereby introducing errors in the results due to lack of consideration of materials that are not used in large quantities (Aversen and Hertwich, 2012). In spite of that, this method is generally considered a reliable approach to calculate the carbon emissions intensity.

The second method is the environmentally-extended input-output analysis (EEIOA) which calculates the emissions intensity using economic data. This method is a top-down approach that treats the entire economy as a system and calculates the emissions cost associated with transactions between various sectors of the economy. The emissions produced are then determined by calculating monetary value produced by each economic sector (Liberman, 2003). This method tends to be more comprehensive but relies on the simplification that each sector produces one average product. Both methods have advantages and disadvantages, however, better accuracy can result by combining these two methods in various processes involved in wind power generation. In a comprehensive literature search we did, we found that of forty three studies, thirty six used process analysis, three used EEIOA, and four used a hybrid of both methods, in which various processes in wind power generation are modeled using either of the two methods depending on the availability of the data for each specific process. The model described in this paper uses a hybrid analysis of various processes involved in wind power generation.

The actual power generated by wind is dependent on two major factors. The first is the size of the turbine. A search of literature shows that there is no linear (or even clear) relationship between the carbon emissions intensity of a wind turbine and its size, (Crawford, 2009), (Lenzen and Munksgaard, 2002), and (Aversen and Hertwich, 2012). Obviously, smaller turbines (below 750 kW) generally have higher emissions intensity with substantial fluctuations. No discernable trend can be found for any range of turbine size. Crawford (2009) found no significant difference in carbon emissions intensity in an 850 kW and a 3.0 MW turbine, with Lenzen and Munksgaard (2002) making the same observation and concluding that small turbines have roughly three times the intensities of larger turbines. Aversen and Hertwich (2012) found a logarithmic drop in intensities for turbines up to 1.8 MW. Our literature review determined a wide range of values for carbon emissions intensity of wind turbines of different sizes. The statistical data on the variation of reported intensities versus turbine size are tabulated in Table 1, showing substantial variation in reported data in the literature. In this study, we have selected a 1.3 MW wind turbine since its various parameters are more readily available in the literature.

Table 1: The range of values found from the wind power LCAs evaluated in literature review of forty three studies done by others.

Distribution Parameters	CO_2 Intensity (g/kWh)
Minimum	3
Mean	13.6
Median	10.7
Maximum	34.4
Standard Deviation	7.76

The second important factor in the power generation of a windmill is its location. Various researchers have performed life cycle assessment of wind power in locations around the world including China (Liang, et. al., 2013), Europe (Tremeac and Meunier, 2009), (Guezuraga, et. al., 2012), and India (Lenzen and Munksgaard, 2002). In a study of renewable potential of the 18 southern states of the U.S., we (Khoie and Yee, 2015) reported a maximum renewable potential of state of Texas with 6,527 billion kWh of renewable resources, most of which in wind energy. As such we have selected the Panhandle of Texas as the location for this study.

3. The Hybrid Model

The model used in this study is a hybrid model in which carbon emissions intensity of various processes in the life cycle of wind turbine are determined using process analysis (PA) for raw materials and the environmentally-extended input-output analysis (EEIOA) for manufacturing, transportation, construction, and overhead/profit operations. We have selected a 1.3 MW Nordex N60/1300kW (Nordex, 2020) wind turbine (80 feet hub height) installed in the Panhandle of Texas. The main specifications of this wind turbine are listed in Table 2.

Table 2: Major specifications of Nordex N-60/1300 kW wind turbine. (Nordex, 2020)

Manufacturer	Nordex
Model	N-60 (80)
Hub Height (m)	80
Rated Power Output (kW)	1300
Rotor Diameter (m)	60
Rotor Swept Area (m^2)	2828
Cut - in Wind Speed (m/s)	3-4
Cut - out wind Speed (m/s)	25

Generated Power: The generated power by a wind turbine is given by Eq. 1: (Kalmikov and Dykes, 2020)

$$P = Cp\frac{\rho A v^3}{2} \qquad Eq. (1)$$

where P is generated power (in W), Cp is the power coefficient (dimensionless with values ranging from 0.25 to 0.45), A is the blade swept area (in m^2) and is the v is the wind speed (in m/s).

Wind Speed: The wind speeds are taken from National Renewable Energy Laboratory using Typical Meteorological Year 3 -TMY3- data (NREL, 2015). Using the specifications provided by Nordex, the power curve of the Nordex N-60 turbine is then calculated as shown in Fig. 4.

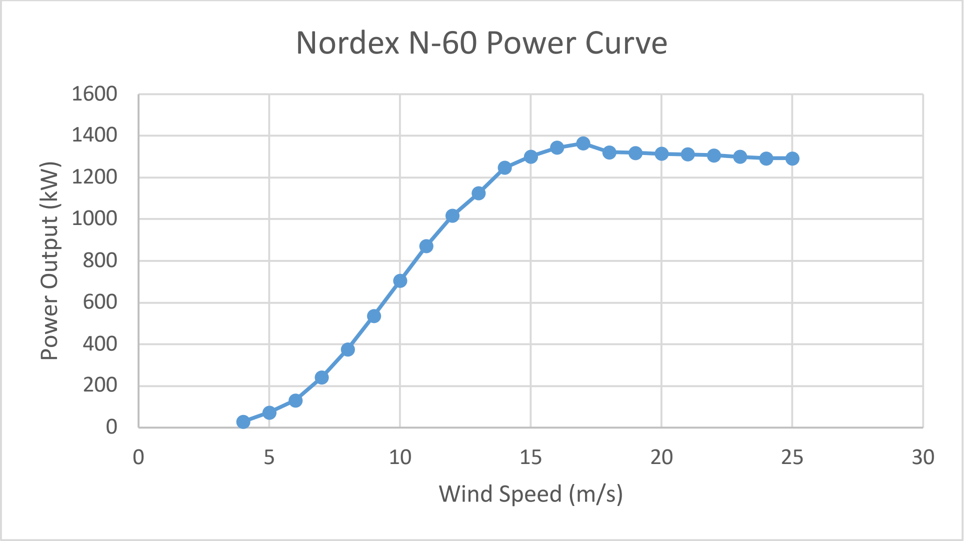


Fig. 4: Power curve of a Nordex N-60 wind turbine, generated power as a function of wind speeds. Data calculated from information provided by (Nordex, 2020).

Total Lifetime Energy Production: The lifetime energy production of the windmill is simply determined from the power curve of the wind turbine as given by Eq. 2:

$$Lifetime\ Energy\ Produced = \left(\sum_{1/1\ 1:00}^{12/31\ 24:00} Power\ Curve(Wind\ Speed) \cdot 3600s \right) \cdot 20yrs \qquad Eq. (2)$$

The variables in Eq. 2 are:

Wind Speed: calculated from TMY3 hourly data.

Lifetime Energy Produced: calculated from Nordex power curve (Fig. 4) multiplied by 3600 seconds in each hour, summed over all the hours starting at 1:00 AM on January 1st ending at 12:00 midnight on December 31st, multiplied by a 20-year lifespan.

Life span of the turbine: taken to be 20 years (Crawford, 2009), (Lenzen and Munksgaard, 2002), and (Aversen and Hertwich, 2012). Using the wind speed data from Amarillo International Airport, the lifetime energy production of the Nordex N-60 wind turbine was determined to be 467 billion KJ.

CO_2 emissions Intensity: Eqs. (3) defines the emissions intensity of the wind turbine:

$$CO_2\ Intensity = \frac{Total\ CO_2\ Produced\ (g)}{Total\ Annual\ Electricity\ Production\ (kWh)} \qquad Eq. (3)$$

The values of total CO_2 produced in various processes are calculated using either process analysis (PA) method or environmentally-extended input/output analysis (EEIOA) as described below.

Process Analysis (PA): is used to determine the CO_2 emissions resulting from the production of **raw materials** used in the wind turbine. In order to perform the process analysis the mass composition of the materials used in Nordex N-60 wind turbine, as well as the CO_2 emissions factors of each raw material are needed. The mass composition of the materials used in construction of the nacelle, rotor, and tower of the wind turbine (Including copper, steel, and glass-fiber reinforced plastic used in blades, hub, transformer, and gear-box) are provided by Liberman (2003). The materials used in the construction of the foundation are primarily concrete and steel rebar, which varies rather significantly based on the soil conditions. Nonetheless, we chose a 350 metric ton concrete which is right at the mean value of the range of 100 to 600 metric ton range of concrete foundations used in installation of the Nordex N-60 turbine. The mass of steel rebar used in the foundation is a dependent on the amount of concrete used. The mass of concrete ranges from 21.8 to 41.5 times the mass of rebar (Liberman, 2003). To study a worst case scenario, we used the 21.8 ratio and determined the mass of rebar to be 16 metric ton. The five primary materials used in the wind turbine are steel, glass-fiber reinforced plastic (GRP), concrete, copper, and oil products. The CO_2 emissions factors of each material were assigned based on various probability distributions (Liberman, 2003) and are tabulated in Table 3.

Table 3 - Assigned CO_2 emissions factors for raw materials used in the wind turbine. (Liberman, 2003)

Material	Assigned CO_2 Emissions Factor (kg CO_2-eq/kg)
Steel	2.5
GRP	3.0
Concrete	0.2
Copper	6.33
Oil Products	1.44

Given the mass composition of materials used in the Nordex N-60 and CO_2 emission factors of each material as shown in Table 3, the emissions are then calculated for each material using:

$$CO2\ Emissions = Mass * CO_2\ \ Emissions\ Factor \qquad (Eq. 4)$$

where *Mass* is the mass of the material (kg), *CO_2 Emissions* are the CO_2 emissions resulting from production of the raw material (g), and *CO_2 Emissions Fact*or is the CO_2 emissions resulting from raw material extraction/refining per unit mass (g CO_2 / kg material). The total emissions from each type of raw material is then summed over all materials used in the turbine.

Environmentally-Extended Input/Output Analysis (EEIOA): is used to determine the CO_2 emissions in various life stages of a windmill based on the cost of various components of the turbine. These components are: **manufacturing, transportation, construction, and overhead/profit.** The CO_2 emissions are given by:

$$CO_2\ Emissions\ (g - CO_2) = \ Component\ Cost\ (\$) * Emissions\ Economic\ Factor\ \left(\frac{g - CO_2}{\$}\right) (Eq. 5)$$

where *Component Cost,* and *Emissions Economic Factor* for select materials are given in Tables 4 and 5 (Liberman, 2003) and (U.S. DOC BEA, 2020). Additional details of the model is presented elsewhere (Khoie, et., al., 2020).

Table 4: Samples of environmental factors in select manufacturing components. (Liberman, 2003)

Manufacturing Sector	CO_2 Emissions Factor (kg- CO_2 /\$)
Transmission Equipment	0.86

Fabricated Steel Plate Work	1.16
Plastics	2.07

Table 5: Unit cost of select materials used in wind turbine. The data shown are mean values reported by others. (U.S. DOC BEA, 2020)

Material	Unit Price ($/mt)
Copper and copper-base alloy	6,340
Steel castings	2,196
Carbon steel, plate, cut lengths	488
Carbon steel, wire rods	387
Lubricating oils	340
Concrete	48.5

Assumptions and Limitations of the Model:
The model used in this study has the following limitations based on either simplifying assumptions or worst case scenarios:

1) Offshore turbines are excluded due to complexities associated with offshore transportation and materials used for foundation.
2) The model assumes an unobstructed turbine, which neglects losses due to a reduction in the kinetic energy of wind as it passes through an entire wind farm.
3) This study assumes the wind turbine is operated as a single unit in the Texas Panhandle. This prevents the additional complexity produced when wind turbines are subject to wake effects caused in a wind farm.
4) We have intentionally chosen worst case scenarios including a 20-year lifespan of the windmill, (as compared to other who have assumed a 25-year lifespan (Kabir, et. al., 2012).
5) The carbon emissions of the following steps in the life cycle of the turbine are not included in our model: connection to the grid, de-commisiong and dismanteling, recycling, and transportation after de-comissioning and landfill. While these steps contribute to the emissions, others have shown them to be either negligible or minor factors, or requiring rather complicated modeling (Aversen and Hertwich, 2012) (Guezuraga, et. al., 2012) (Martinez, el. al., 2009).

4. Results

The results of the Process Analysis model for environmental impacts of production of raw materials used in a 1.3 MW wind turbine (the turbine and its structure) are shown in Table 6. The total emissions for production of raw materials is 715 Mg - CO_2, with steel being the biggest contributor.

Table 6: Total CO_2 emissions (Mg- CO_2) for raw materials determined from PA model.

Material	Total CO_2 Emissions (Mg- CO_2)
Steel	558
Glass fiber Reinforced Plastic	72.3
Concrete	70
Coper	12.6
Oil Products	1.81
Total Raw Materials (PA Model)	715

The results of EEIOA model for transportation, construction, overhead/profit, and manufacturing are listed in Table 7. As shown in Table 7, the transportation, construction, overhead/profit, and manufacturing are responsible for 307, 72.6, 10.9, and 765 Mg- CO_2 emissions, respectively, during the 20-year lifespan of the windmill. Table 8 shows the results of total emissions for all processes in the 20 years lifespan of a 1.3 MW windmill operating in Panhandle of Texas.

Table 7: Total CO_2 emissions (Mg- CO_2) for major wind turbine components (other than raw materials) determined using EEIOA model.

Major Components	Sub - Component	Total CO_2 Emissions (Mg- CO_2)
Transportation	Sea Freight	174
	Truck	133
Construction	Site Prep	7.56
	Remote Monitoring	7.56
	Erection/Commissioning	22.7
	Foundation	34.8
Overhead/Profit	Overhead	10.9
Manufacturing	Mechanical Power Transmission Equipment	340
	Fabricated Plate Work	153
	Plastics Materials Resin	272
Total	**(EEIOA Model)**	**1,155.52**

Table 8: The results of total CO_2 emitted by a 1.3 MW wind turbine operating in the Panhandle of Texas for 20 years.

Material	Total CO_2 Emissions (Mg- CO_2)
Raw Materials (PA Model)	715
Manufacturing, Transportation, Construction, and Overhead/profit (EEIOA Model)	1,155.52
Total (Lifetime)	**1,870.52**
Total (Annual)	**93.53**

Table 9: The summary of results of CO_2 emissions intensity of a 1.3 MW wind turbine operating in the Panhandle of Texas for 20 years. Also included are those of a similar average coal power plant (Liang, et. al., 2013).

Energy	Total Energy Output (TJ)
Annual Energy Output	23.3 TJ/Year = 6,472,222 kWh/Year
Lifetime (20 Years) Energy Output	**466 TJ/Lifetime = 129,444,444 kWh/Lifetime**
Intensities	**Amount/Total Energy Output**
CO_2 Emissions Intensity (Wind)	1,870.52 Mg CO_2/466 TJ = **14.45 g-CO_2/kWh**
CO_2 Emissions Intensity (Coal) (Liang, et. al., 2013)	792 g-CO_2/kWh

Table 9 shows these results in terms of CO_2 emission intensity. With an annual electricity production of 23.3 TJ/Year, a 1.3 MW windmill in a location near the Amarillo International Airport produces 466 TJ of electricity

(129,444,444 kWh) operating over 20 years. The lifetime CO_2 emissions of this windmill is 1,870.52 Mg- CO_2 resulting in emissions intensity of 14.45 g- CO_2 /kWh, respectively.

Compared to the average CO_2 emissions intensity of coal generated electricity of 792 g-CO_2 /kWh (Liang, et. al., 2013) and (Tang, et. al., 2014), this winwill produces only 1.82% emissions of a similar size coal power plant, which is while substantial (98.2%) savings in emissions, it is not insignificant, especially with high penetration of wind energy in elecricity sector in the coming decades. Our result, while in general agreement with those reported by others, is higher than the mean value of 13.6 g-CO_2 /kWh for emissions intensity.

5. Conclusions

The results of this study shows that a 1.3 MW Nordex N-60 wind turbine operating near the Amarillo International Airport (in Panhandle of Texas) has carbon dioxide intensity of 14.45 g- CO_2 /kWh, respectively. When compared to the carbon dioxide intensity of 13.6 g - CO_2/kWh, reported by others, our model overestimates carbon emissions by 6.6%. This difference is in large part due to the assumptions we have made in our model as listed above. Compared to coal power plants the wind turbine studied here emits 1.8% of carbon dioxide.

For the twelve months ending September 2019, the United States generated 286.6 terawatt-hour of wind power, roughly 7% of all generated electricity (Wind Power Monthly, 2020A). Our study shows that this wind generation in 2019 has produced roughly 4.13 million tons (MT) of CO_2 emissions, which is 98.2% less emissions than if this power had been generated from coal power plants. Nonetheless, this 4.13 MT emissions needs to be removed from the atmosphere, for the wind power to be truly carbon neutral. With the projected deeper penetration of wind in the U.S. electricity portfolio, the issue of emissions by wind power will become even more pressing, especially if the goal is to remove carbon from the atmosphere as suggested in 2018 by the National Oceanic and Atmospheric Administration.

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