Life cycle energy analysis and ecological impact of wind turbines - a comparison of life cycle assessments

*Lars Goray**

FH Münster, Stegerwaldstraße 39, 48565 Steinfurt

Abstract

The use of wind power is rapidly expanding worldwide. It is important to examine the impact of wind turbines on the environment to see if they provide a net benefit and to identify potential for improving. Therefore life cycle assessments (LCA) of different wind turbine types are compared in this short review. The results are then shown side by side in tables for comparison. Overall the LCAs show that wind turbines compensate the required energy and emitted pollutants after approx. 6-16 months. The energy payback period (EPP) for 2 MW onshore wind turbines remained roughly the same since 2009 with approximately 7 months. Onshore wind turbines have a higher impact due to emissions but a shorter EPP than offshore wind turbines. The estimated service life of 20 years should be maximized to ensure a high energy yield ratio. The biggest impact on the environment results from the processes to provide the building material e.g. steel and cement. That impact could be reduced by 20 % if recycled steel would be used. It is shown that wind power is one of the cleanest energy sources. But further investigations in material processing and recycling are important to improve the eco-balance of wind turbines.

Keywords: wind turbine, wind power, regenerative energy, life cycle assessment, energy analysis, ecologic, environmental impact

Abbreviations

CO_2PP	CO_2 payback period
CHP	combined heat and power plants
DDPMSG	direct drive permanent magnet synchronous generator
DDSG	direct driven synchronous generator
DFIG	doubly-fed induction generator
EPP	energy payback period
EYR	energy yield ratio
GRP	Glass fibre reinforced Plastic
I-O	input - output
LCA	life cycle assessment
Pt	eco-points

(Abbreviations of the impact categories in Tab. 4 are listed below the table.)

1 Introduction

Because of the increasing transition to renewable energy sources and demand for independency from fossil fuel suppliers, wind power is rapidly developing worldwide. 93.6 GW new wind power capacity was added worldwide in 2021. Which brings the total installed capacity to 837 GW. Compared to 2020 that is a growth of 12.4 %.[1] Considering this rapid growth, it is important to examine the impact on the environment to ensure that wind turbines are providing a net ecological benefit and to analyse if the processes of the wind turbine life cycles are improving.

This article compares different life cycle assessments of wind turbines to answer the questions,

- how clean wind energy actually is,
- which aspects of the wind turbine life cycle affects the environmental impact the most and
- how the life cycle can be improved.

*Corresponding author: lars.goray@fh-muenster.de

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2 Methodology

The Information in this article was gathered by literature research via the internet. The search engines Google Scholar and FINDEX, a service provided by the library of the University of Applied Sciences FH Muenster, were used to find scientific articles. To ensure that important information on the subject area is considered, the most cited sources were used. In order to also cover recent developments, additional articles were picked out with the search scope set to 2018-2022. Different English keywords were used e.g. "wind turbine life cycle","wind turbine energy analysis", "wind turbine recycling". Additional information was gathered from the citations of the used articles and the search engine DuckDuckGo.

The LCAs of wind turbines mainly focus on energy analysis and emission of pollutants. The result of each article is briefly summarized. All results are put together in two tables (energy and emission) for comparison. Other impacts like visual and acoustic pollution, avian collision with birds, insects etc. and pressure waves during offshore installation are not subjects of the LCA. These are also important factors in the whole picture of wind turbines but the coverage of all impacts would be to big for the scope of this short review.

3 Life cycle assessment of different types of wind turbines

To get an idea of the structure of a wind turbine, Fig. 1 shows a wind turbine with coloured main components. Tab. 1 shows the material use per item of the components for the 850 kW and 3 MW wind turbines, used in the Life cycle assessment by Crawford [2]. Tab. 2 shows the total material consumption.

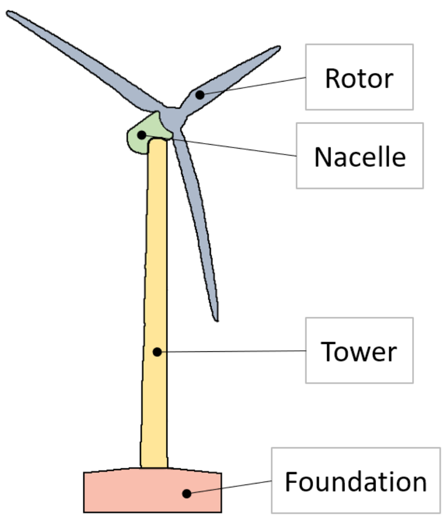

Fig. 1: Main components of a wind turbine (own image)

It is not possible to formulate a precise general statement on the benefits and ecological impact of wind turbines, because life cycle analyses depend on many different factors. First there are different tools and methods to quantify the embodied energy and emitted pollutants associated with provision of materials, transportation, manufacturing, operation, maintenance and disposal. Traditional methods are process analysis and input-output (I-O) analysis. There are also a variety of hybrid methods, combining process and I-O data, which try to minimise the errors and limitations. Errors and limitations mainly result from complex supply chains and difficulties of obtaining necessary information. Every LCA also makes different simplification and assumptions. Therefore some inputs can be incomplete or neglected. A system boundary, as seen in Fig. 2, helps to keep an overview of all in- and outputs. [2]

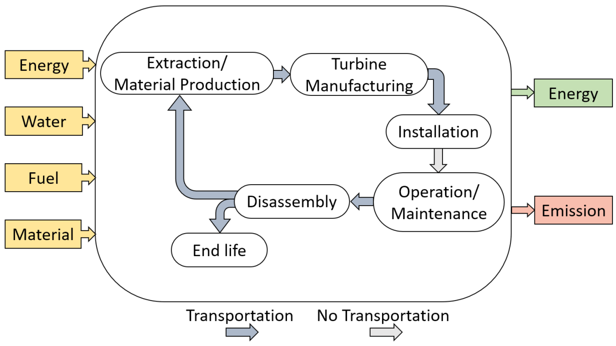

Fig. 2: Example of a System Boundary (own image, modeled after Chipindula et al.[3])

Furthermore the embodied energy and emitted pollutants during manufacturing etc. are affected by the type of wind turbine (on-/offshore), type of generator and wind turbine size [3–5]. The wind turbine size also affects the energy generation and final energy yield [2]. Energy generation and the final energy yield also depend on the conversion efficiency of the generator, wind levels at the specific location and the service life of the wind turbine, which is generally assumed to be 20 years [2–4].
Because LCAs as well as wind turbines are diverse, the results of different LCAs from 2009 to 2019 were compared. The result of each LCA is briefly described in section 4. The specifications of all assessed wind turbines are listed in Tab. 3.
Some authors analysed the energy need for manufacturing etc. and compared it to the energy yield of the wind turbine, while others focused on toxic chemicals and emission during the life cycle of the wind turbine. Therefore the gathered articles can be distinguished in two categories; life cycle energy analysis and ecological impact analysis on humans and the environment. Tab. 4 shows the results for the ecological impact analyses and the results for the life cycle energy analyses are listed in Tab. 5 for comparison.

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Tab. 1: Component breakdown and material use of wind turbines, modeled after LCA by Crawford [2]

		850 kW	3 MW
Component	**Item**	**Materials**	**Materials**
Foundation	Reinforced concrete	480 t concrete	1140 t concrete
		15 t steel	36 t steel
Tower	Painted steel	69.07 t steel	158.76 t steel
		0.93 t paint	1.24 t paint
Nacelle	Bedplate/frame	3.35 t steel	13 t steel
	Cover	2.41 t steel	9.33 t steel
	Generator	1.47 t steel	5.71 steel
		0.37 t copper	1.43 t copper
	Main shaft	4.21 t steel	
	Brake system	0.26 t steel	1.02 t steel
	Hydraulics	0.26 t steel	
	Gearbox	6.08 t steel	23.58 t steel
		0.0062 t copper	0.241 t copper
		0.062 t aluminium	0.241 t aluminium
	Cables	0.18 t aluminium	0.69 t aluminium
		0.24 t copper	0.94 t copper
	Revolving system	1 t steel	3.87 t steel
	Crane	0.26 t steel	1.02 t steel
	Transformer/sensors	0.894 t steel	3.47 t steel
		0.357 t copper	1.38 t copper
		0.357 t aluminium	1.38 t aluminium
		0.18 t plastic	0.7 t plastic
	Total	20.194 t steel	61 t steel
		0.9732 t copper	3.991 t copper
		0.599 t aluminium	2.311 t aluminium
		0.18 t plastic	0.7 t plastic
Rotor	Hub	4.8 t steel	19.2 t steel
	Blades	3.01 t fibre glass	12.04 t fibre glass
		2.01 t epoxy	8.03 t epoxy
	Bolts	0.18 t steel	0.73 t steel

Tab. 2: Total material consumption of the wind turbines in the LCA by Crawford [2]

0.85 MW	**3 MW**
480 t concrete	1140 t concrete
109.24 t steel	275.69 t steel
0,93 t paint	1,24 t paint
0.97 t copper	3.99 t copper
0.60 t aluminium	2.31 t aluminium
0.18 t plastic	0.7 t plastic
3.01 t fibre glass	12.04 t fibre glass
2.01 t epoxy	8.03 t epoxy

The life cycle energy analysis examines all energy flows over the entire life of the wind turbine. The embodied energy generally consists of energy required for the processing of building material, manufacturing, transportation, construction, installation and ongoing maintenance. [2, 6] With the embodied energy and the energy generation the energy payback period (EPP) can be calculated. Alternatively the energy yield ratio (EYR) can be calculated, by dividing the Energy generated over the wind turbines entire life by embodied energy. Contrary to the EPP the EYR takes the entire life of a product into account. Therefore Crawford [2] suggests, that the energy yield ratio offers better information. But many LCAs traditionally use the EPP method. [2]

The ecological impact analysis examines all pollutant emissions and other impacts in the environment and humans over the entire life of the wind turbine (cradle to grave). Traditionally the following stages are taken into consideration:

1. manufacture of each component part
2. transport to the wind farm
3. installation
4. start-up

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5. maintenance
6. final decommissioning and disposal

But every LCA takes different assumptions and simplifications. The impact categories do also vary, but generally follow the Eco-indicator 99 or Impact 2002+ method [7]. The impact is generally presented in Eco-points (Pt). Eco-points are used to normalize data. But some authors give the information in kg pollutant equivalent. Chipindula et al.[3] differentiate between aquatic and terrestrial ecotoxicity and acidification/eutrophication but for simplification the categories are put together in Tab. 4. The Impact categories in this review paper consist of:

- carcinogens
- non-carcinogens
- respiratory inorganics
- respiratory organics
- radiation
- global warming
- ozone layer depletion
- ecotoxicity
- acidification and eutrophication
- land use
- minerals
- fossil fuels

4 LCA results

In this section the results of each LCA is briefly summarized. All results are then compared side by side. Tab. 4 shows the results for the ecological impact analyses and the results for the life cycle energy analyses are listed in Tab. 5 for comparison. Fig. 5 illustrates the EPP of the wind turbines listed in Tab. 5. The specification of the examined wind turbines are listed in Tab. 3.

Crawford (2009) [2] examined what influence the wind turbine size has on the energy yield ratio, since "there is an increasing trend towards larger scale wind turbines"[2]. Therefore the EYR of a 850 kW and a 3 MW wind turbine are compared. For an expected service life of 20 years the EYR is 21 for the 850 kW and 23 for the 3MW wind turbine. So after 20 years the turbines have generated 21 and 23 times more energy, than needed for manufacturing etc. The EYRs increase to 32 and 35 for an expected service life of 30 years. So the benefits increase with increasing service life. The larger 3 MW wind turbine shows an 11% higher EYR, which is not considered to be significant. Because the EYR method was used, the energy payback period is estimated in Tab. 5 to allow comparison to other LCAs.

Martínez et al. (2009) [6] examined which component of the wind turbine has the biggest environmental impact. ISO 14040 and Eco-indicator 99 methods are used. The foundation affects the environment the most, especially in the respiratory inorganics category, due to the cement manufacture. So it is important to find ways to reduce air emissions of particle matter, SO_2 and NO_X. The steel of the tower can almost completely be recycled. The nacelle is the most complex component and consists of many different materials, of which copper has the biggest impact. Although it is recyclable, it would be an improvement to replace it with another material with similar characteristics without reducing the generator efficiency. The energy analysis of the same turbine was published in a different article, which results in an EPP of 0.58 years and an EYR of 34.36 [9].

Chipindula et al. (2018) [3] examined the ecological impact of three hypothetical wind farms. Onshore with capacites of 1 MW, 2 MW and 2.3 MW, offshore in shallow water with 2 MW and 2.3 MW and offshore in deep water with 2.3 MW and 5 MW. The material extraction/processing is the critical stage responsible for 72 % contribution of impact onshore, 58 % in shallow water and 82 % in deep water. The recycling of steel could lower the average impact across all impact categories by 20 %. The EPP and CO_2PP in Tab. 5 are estimated from bar charts.

Schreiber et al. (2019) [5] evaluated the environmental impact of three 3 MW wind turbines with different generator at a fictive onshore site in Germany. The three generator types are:

- geared converter with doubly-fed induction generator (DFIG)
- direct driven synchronous generator (DDSG) electrically excited
- direct drive permanent magnet synchronous generator (DDPMSG)

The DDSG nacelle weight is one third greater then that of the DFIG and more than two thirds greater than that of the DDPMSG. Due to the massive construction, the DDSG shows the highest impact in 14 out of 15 impact categories. Construction materials are the significant source of impact. The DDPMSG is lighter than the other wind turbine types and therefore requires less steel and cement. The permanent magnet production on the other hand requires rare earths and despite of its weight (1.9 t) accounts for approx. 43 % of the overall impacts compared to 108 t steel, stainless steel and copper with an accumulated share of approx. 52 %.

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Tab. 3: Specification of all considered wind turbines, information from [2–6, 8]

WT	LCA Source	Power in MW	On-/ Off-shore	Generator Specification	Location
1	Crawford(2009) [2]	0.85	on	-	Australia
2	Crawford(2009) [2]	3	on	-	Australia
3	Martínez et al.(2009) [6, 9]	2	on	DFIG	Spain
4	Guezuraga et al.(2012) [4]	1.8	-	not-geared	Austria*
5	Guezuraga et al.(2012) [4]	2	-	geared	Austria*
6	Chipindula et al.(2018) [3]	1	on	-	Texas, USA
7	Chipindula et al.(2018) [3]	2	on	-	Texas, USA
8	Chipindula et al.(2018) [3]	2.3	on	-	Texas, USA
9	Chipindula et al.(2018) [3]	2	off/ shallow	-	Texas, USA
10	Chipindula et al.(2018) [3]	2.3	off/ shallow	-	Texas, USA
11	Chipindula et al.(2018) [3]	2.3	off/ deep	-	Texas, USA
12	Chipindula et al.(2018) [3]	5	off/ deep	-	Texas, USA
13	Schreiber et al.(2019) [5]	3	on	DFIG	Germany
14	Schreiber et al.(2019) [5]	3	on	DDSG	Germany
15	Schreiber et al.(2019) [5]	3	on	DDPMSG	Germany
16	Piasecka et al.(2019) [8]	2	on	-	Poland*
17	Piasecka et al.(2019) [8]	2	off	-	Poland*

DFIG: Doubly-fed induction generator; DDSG: Direct driven synchronous generator; DDPMSG: Direct drive permanent magnet synchronous generator; * if wind turbine location is not specified, the authors location is assumed

Tab. 4: Environmental impact results for different wind turbines, information from [3, 6, 8]
black: normalized data in eco-points (pt)
blue: unnormalized data in given unit

WT	C	NC	RI	RO	R	GW	OZ	ET	A/E	LU	M	FF
	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt	Pt
3	322	-	28041	29	16	2350	7	3156	2117	2951	46	26902
16	7000*	-	31528	-	<1000*	9138	<1000*	9860	3000*	1500*	12208	58004
17	8000*	-	24846	-	<1000*	9875	<1000*	10297	2000*	1500*	11996	41713
	kg C_2H_3Cl eq.	kg C_2H_3Cl eq.	kg $PM_{2.5}$ eq.	kg C_2H_4 eq.	bq C14 eq.	kg CO_2 eq.	kg CFC11 eq.	kg TEG	kg SO_2 eq. + PO_2H_4 P-lim	m^2 organic arable land	MJ	MJ
6-8	30	23	9×10^{-1}	2×10^{-1}	4663	440	5×10^{-5}	67827	12	7	223	6578
9,10	90	59	3	8×10^{-1}	10197	1144	10×10^{-5}	245510	32	21	590	16115
11,12	80	63	2	3×10^{-1}	8838	648	10×10^{-5}	247781	27	15	702	10930

WT = Wind Turbine; C = carcinogens; NC = non-carcinogens; RI = respiratory inorganics; RO = respiratory organics; R = Radiation; GW = global warming; OZ = ozone layer depletion; ET = ecotoxicity; A/E = acidification and eutrophication; LU = land use; M = minerals; FF = fossil fuels; *estimated from diagram

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Guezuraga et al. (2012) [4] compared the life cycle of a geared 2 MW wind turbine to a non-geared 1.8 MW wind turbine. The environmental impacts per kWh electricity delivered of the wind turbines are very similar. Because the geared 2 MW wind turbine has a higher initial energy need but also generates more energy. The energy payback period is 0.52 years for the geared 2 MW wind turbine and 0.58 years for the 1.8 MW wind turbine. Furthermore a comparison is made between wind energy and other sources of energy:

- Photovoltaic plants - amorphus, monocrystalline and polycrystalline silicon
- Hydropower plant
- Nuclear power plant (pressurized water reactor, auxiliary electricity required from diesel system, enriched uranium as fuel input)
- Gas cogeneration plant (large scale gas fired combined cycle cogeneration plant, low NOx burner fed with natural gas, credit allocated from cogeneration heat from combined heat and power plants (CHP) replaces gas heating)
- Coal power plant (hard coal as fuel)

Fig. 3 shows the CO_2 equivalent emissions per kWh produced energy. The energy payback period of the different energy sources can be seen in Fig. 4. Wind and hydro power turn out to be the cleanest energy sources.

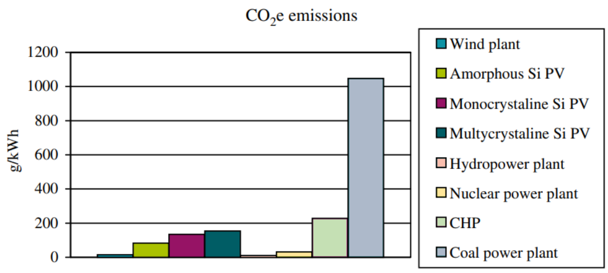

Fig. 3: CO_2e emissions/ kWh for different energy sources [4]

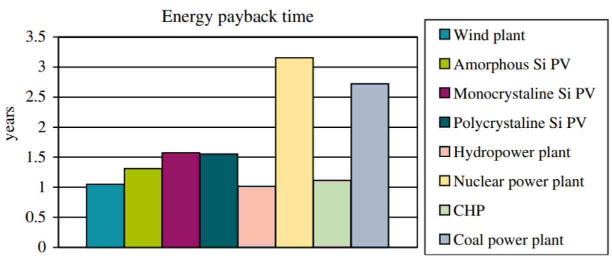

Fig. 4: Energy payback period for different energy sources [4]

Piasecka et al. (2019) [8] compared the ecological impacts of a 2 MW offshore wind turbine to a 2 MW onshore wind turbine. The onshore wind turbine has a bigger accumulated impact (125147 Pt) than the offshore wind turbine (109075 Pt). The processes connected with fossil fuel extraction (FF in Tab. 4) and emission of compounds causing respiratory diseases (RI in Tab. 4) have the largest influence.

Tab. 4 and Fig. 5 show that onshore wind turbines have a higher impact due to emission but a shorter EPP. Furthermore turbines with higher power have usually a shorter EPP. It can be seen from the course of the 2 MW turbine in Fig. 5 that the efficiency of wind turbines stayed the same since 2009 with an EPP of approx. 7 months for onshore 2 MW wind turbines. The high EPP for the 0.85 MW and the 3MW wind turbine in 2009 can be explained by the fact that the values were only estimated using the EYR.

Tab. 5: Energy payback period and CO_2 paypack period results for different wind turbines, information from [2–5, 8, 9]

Wind Turbine	EYR	EPP in months	CO_2PP
1	21.0	11.4*	-
2	23.0	10.4*	-
3	34.36	7.0	-
4	-	6.2	-
5	-	7.0	-
6	-	15.5**	7.0**
7	-	7.5**	6.3**
8	-	6.2**	5.8**
9	-	16.7**	14.0**
10	-	13.0**	10.8**
11	-	11.0	8.7**
12	-	9.6	7.2*

*estimated, **estimated from graph

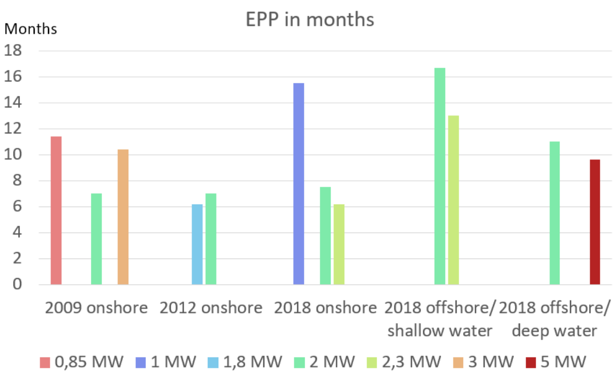

Fig. 5: Energy payback period for different wind turbines (own image, information from [2–5, 8, 9])

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5 Recycling

The recycling of wind turbine components and material has a significant impact on the LCA. As stated in section 3, the recycling of steel could lower the average impact across all impact categories by 20 % [3]. Guezuraga et al. (2012) [4] state that "80 % of a wind turbine system (including cables) can be recycled, except the blades which are made of composite materials and the foundation which is made of concrete" [4].
The turbine blades are difficult to recycle because they are made out of resin and glass fibre reinforced plastic (GRP). Possible recycling methods for the problematic turbine blades include the following [10]:

- mechanical shredding and separation into resin and fibrous products
- pyrolysis at 450°C-700°C: polymeric resin vaporizes while fibres remain inert and can be recovert
- oxidation in fluidised bed at 450°C-550°C: Combustion of the composite material in hot air flow to separate resin and fibres
- chemical: resin decomposes in chemical solution into oils, while fibres stay intact

GRP can be shredded and burned in cement kilns as the glass reinforcement and mineral fillers used in composites contain minerals that can be incorporated in cement [11]. This method is available in Germany since 2011 [12]. Zajons Zerkleinerungs GmbH provided shredded GRP to Holcim AGs cement kilns in Lägerdorf. But Zajons Zerkleinerungs GmbH has become insolvent in 2015 [13]. Another German Company recycling GRP is Neocomp in Bremen, which now provides Holcim [14]. Only a few other Companies worldwide are dealing with the recycling of GRP e.g. Eco-Wolf and Global Fiberglass Solutions [12].

Nagle et al. (2020) [15] examined the recycling possibilities of Irish wind turbine blades. It was found out that transportation and co-processing in a German cement kiln is six times better (for the environment) than depositing the blades in an Irish landfill. The theoretical co-processing in Ireland at a 10 % substitution rate would be 1007 % better than landfilling in Ireland and 78 % better than transportation and co-processing in Germany [15].
Jensen [16] examined a potential recycling of a 60 MW wind farm in Denmark. A 100 % recycling rate would lead to energy savings of approximately 81 TJ and emission reduction of 7351 t CO_2. To put the numbers in perspective, 81 TJ is the equivalent of the annual energy consumption of approximately 14400 persons in Denmark. 7351 t CO_2 savings equal around 52.5 million km of car driving, assuming an average emission of 0.17 kg CO_2/km. [16]

So it is worthwhile to further investigate recycling options, as it is beneficial for the environment and also profitable to save material and energy during production.

6 Conclusion

The various life cycle assessments are not always easy to compare due to different assumptions and used methods. Visual and acoustic pollution as well as avian collision with birds, insects etc. and pressure waves during offshore installation are not taken into account in LCAs. With the rising development of wind energy these aspects are also important to investigate. But overall the LCAs show that the energy payback period for wind turbines is approx. 6-16 months. The EPP for 2 MW onshore wind turbines remained roughly the same since 2009 with approx. 7 months. The CO_2 payback period is approx. 6-14 month. So after 6-16 months wind turbines compensate the embodied energy and their negative impacts on the environment and produce clean energy. The service life is important for the total energy yield. With an estimated service life of 20 years and an energy payback period of 12 months a wind turbine produces 20 times more energy than required for manufacturing etc. Chipindula et al. [3] show that wind and hydro power are the cleanest energy sources. The LCA of wind turbines would even be better, if energy required in material processing and manufacturing would be regenerative energy or if the process of material provision e.g. steel production would be more efficient. Recycling is also an important factor. Most of the materials can already be recycled but the blades and the foundation are still a problem. Another solution for the problematic blades would be to examine if other materials than resin and GRP are suitable for wind turbine blade manufacturing. So further investigations in recycling methods and material processing are important to improve the already good eco-balance.

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