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Life Cycle Environmental Impact of Wind Turbines: What are the Possible Improvement Pathways?

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Abstract. This study explores the effect of different technology choices on the life cycle Greenhouse Gases (GHG) emissions of wind turbines. It aims at identifying possible improvement pathways and quantifying potential benefits. First, an automated Life Cycle Assessment (LCA) model is developed and validated against other studies. The breakdown of the resulting Impact Of Energy (IOE) by life stages, components and materials is presented for a selected reference turbine. Sensitivity analyses are conducted on the different hypotheses to model the turbine life cycle. The model is then applied to analyze the potential effect of turbine size, foundation type, tower type, drivetrain technology, carbon-fiber blades and thermoplastic polymer resin for the blades. The tower type (especially wooden tower) and the thermoplastics (allowing to recover materials at the end-of-life) are identified to have the biggest potential to reduce the life cycle environmental impact of wind energy.

1. Introduction

The assessment of wind turbine technology is most commonly driven by minimizing the Levelized Cost of Energy ($LCOE$), which has allowed a drastic decrease in costs of wind energy in the last years. But as climate change awareness is rising, costs are not the only criterion anymore for the choice of an electricity production technology. This work introduces considerations about the life cycle environmental impact, limited to climate change impact through the emissions of Greenhouse Gases (GHG), as a new complementary merit to be minimized. Compared to fossil-fired electricity generation, wind turbines cause no direct emissions. But from a life cycle perspective, opportunities for improvement can be found. Life Cycle Assessment (LCA) is a normed method to assess the environmental burdens of a product over its entire lifetime. It has been applied to wind energy in various publications [16, 20, 9, 1, 13, 8] that, however, assess existing (i.e., already designed) configurations. This work proposes to include an LCA approach as early as in the preliminary technology choices for a turbine. The objectives are to identify which turbine components and materials have the highest environmental burden, and to quantify possible improvement pathways.

First, an automated model is formulated to assess the Impact Of Energy (IOE) for any turbine configuration. The approach is presented in Section 2. The model is applied to estimate the environmental impact of a reference wind turbine, presented in Section 3, where the components that have the highest contribution are identified. In Section 4, parametric studies are realized to quantify how this impact can be decreased by several alternative technologies. Finally, Section 5 summarizes the main findings and their limitations, and offers a look into future development.

2. Approach

2.1. Framework of the automated LCA model

A general model is developed to assess IOE for any given turbine configuration (rated power P_{r}, rotor diameter RD, hub height HH, technology choices), and wind resources (i.e. site conditions). The general framework is schematized on Figure 1.

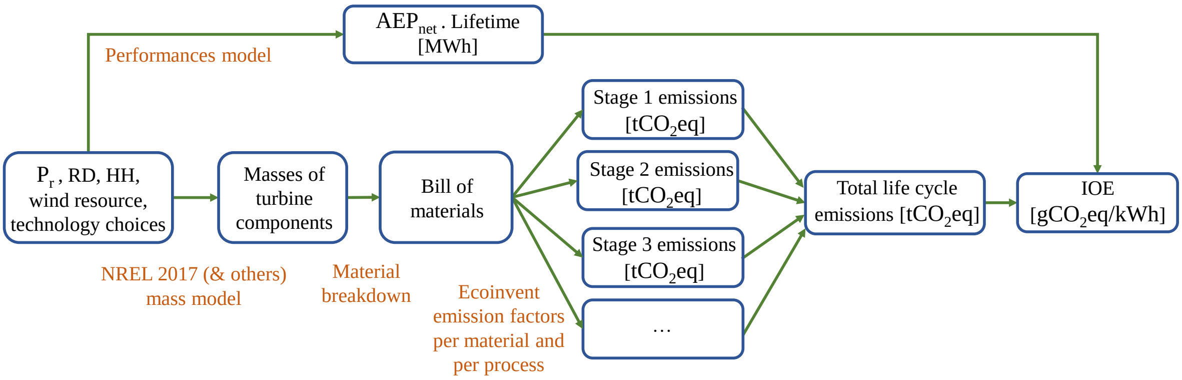

Figure 1. Schematic representation of the automated wind turbine LCA model.

The turbine reference static power curve $P_{\mathrm{electr}}(V)$ varies with rated power and rotor diameter. The wind Weibull distribution $w(V)$ varies with the selected average wind speed at a given site, as well as with the hub height according to a shear power law with exponent 0.2. The net Annual Energy Production (AEP_{net}) is then estimated as

$$AEP_{\mathrm{net}} = AF \cdot PF \cdot Y \cdot \int_{V_{\mathrm{cut-in}}}^{V_{\mathrm{cut-out}}} w(V)\, P_{\mathrm{electr}}(V)\, dV, \tag{1}$$

where $Y = 8760\, hours$. Two correction factors are applied to consider realistic energy yield:

- Availability Factor (AF): represents failure, maintenance and curtailment time. A value of 98% is considered from an industry review [14].
- Performance Factor (PF): represents the dynamic losses, elasticity losses, the turbulence and gust losses, and the wake losses. A value of 65% is considered from ref. [5].

2.2. Estimation of the bill of materials

For a given turbine configuration (P_{r}, RD, HH, technology choices), the masses of the turbine components are determined based on the NREL mass model 2017 [21], except for the tower mass that is interpolated using data from ref. [6], and the drivetrain (gearbox, generator and converter) masses that are interpolated using data from ref. [11]. The last two sources are used to compare the environmental impact of different technology alternatives (Section 4). For assessing the environmental impact, a detailed bill of materials must be determined. The material breakdown presented in Table 1 is sourced from the literature [13, 9, 15, 8] for the reference technology configuration (see Section 3.1). Waste factors are also modeled according to [21].

2.3. Description of the LCA model

The LCA model is formulated according to widely recognized general procedures [10]. It is developed based on various sources of LCA applied to wind energy [16, 20, 9, 1, 13, 8], crossed with cradle-to-gate emission factors from Ecoinvent [19].

Table 1. Material breakdown (mass fractions by columns) and waste factors considered.

	Blades	Hub	Gearbox	Generator	Converter	Nacelle	Tower	Foundations	Waste factors
Glass fibers	52%					1.95%			10%
Epoxy resin	28%					1.05%			20%
Sandwich foam	5%								20%
Alloyed steel	3%		96%	94.8%					5%
Unalloyed steel		91%				84%	95%	4%	5%
Galvanised steel							3%		5%
Copper			2%	5.2%		4%			5%
Aluminium	0.6%	9%	2%			7.02%			5%
PVC and plasts	7%					1%			5%
Rubber	1%								10%
Paint and coating	3.4%					0.98%	2%		25%
Electronics					100%				5%
Concrete								96%	5%

- **Goal definition:** This LCA study aims at assessing the whole life cycle GHG emissions associated with wind energy in a general automated way that can be applied to any turbine configuration. The model is used to identify the main sources of environmental burden and quantify potential improvement opportunities.
- **Scope definition:** The studied system is a large-scale onshore variable-speed horizontal-axis wind turbine. It is assumed to be installed in Germany between 2015 and 2025 (scope of emissions data from Ecoinvent [19]). The considered system includes the components presented in Table 1. The selected Functional Unit (FU) is 1 kWh of electricity extracted from a single turbine. This study focuses on the climate change environmental impact category. Eight life stages are considered as detailed in Section 2.4.
- **Life Cycle Inventory (LCI):** Based on the bill of materials, the LCA database Ecoinvent is used to approximate the life cycle of a turbine by means of reference processes and activities, including peer-reviewed emission factors, i.e. GHG emissions per unit of mass [19].
- **Life Cycle Impact Assessment (LCIA):** IPCC 2013 is the selected Ecoinvent LCIA method which assesses the climate change environmental impact by means of global warming potential, expressed in $kgCO_2eq$ (including all recognized GHG) [19, 3].
- **Limitations:** The need for generality in order to study different turbine configurations on a common framework introduces limitations on IOE confidence. The estimation of the bill of materials, the emission factors from Ecoinvent and hypotheses to model the life stages bring uncertainties, that are quantified in Section 3.2.
- **Impact Of Energy used:** IOE is defined as the sum of all GHG emissions that occur during the turbine life cycle, divided by the expected energy production over the lifetime.

2.4. Modeling of the turbine life stages

The different life stages are here described, including the assumptions considered.

Stage 1: Raw material extraction and processing. The mass of each material is multiplied by the corresponding cradle-to-gate emission factors from Ecoinvent [19], which contain all impacts upstream of purchasing ready-to-use materials.

Stage 2: Transportation of materials. Direct and indirect transportation emissions are included from Ecoinvent [19]. All materials are assumed to be transported 600 km by truck to the manufacturing site, except for concrete which is only transported 50 km [8].

Stage 3: Manufacturing of turbine components. The manufacturing causes indirect emissions from energy consumption of industrial processes, as well as related direct emissions.

Manufacturing impacts for most materials are taken from ref. [19], except for blades made of glass-fiber reinforced polymers (GFRP) which are sourced from ref. [18] considering Vacuum Assisted Resin Transfer Molding (VARTM).

Stage 4: Transportation of components. A representative scenario is considered from ref. [8]. The blades are transported 1900 km by ship and 900 km by truck. The hub elements travel 3100 km by ship and 300 km by truck. The drivetrain and other nacelle elements are transported 800 km by truck. The tower is transported 4500 km by ship and 500 km by truck.

Stage 5: Turbine installation. The installation is modeled as the utilization of an hydraulic crane for 16 hours of work per turbine, from ref. [13, 15].

Stage 6: Operation and maintenance (O&M). The consumption of gearbox lubricant is considered from ref. [9, 13, 15]. An inspection van does a roundtrip of 120 km every 6 months [13] and 8 hours of crane work model the lifetime maintenance. Furthermore, this stage includes the replacements of failing components. It is considered that one whole blade, one whole gearbox, 50% of the pitch system and bearings, and 15% of the converter and remaining nacelle components need to be replaced over the lifetime [20, 9, 13]. The impact of the raw materials, manufacturing and transportation of the replaced components is included here.

Stage 7: Decommission. 16 hours of an hydraulic crane work are considered. The transportation of parts is also included (using the same distances using trucks and ships as in stage 4).

Stage 8: End-Of-Life (EOL). The recycling of most of the metals is in widespread adoption for wind turbines. Metal components are assumed to be 90% recycled and 10% landfilled [20, 9, 8]. Negative emissions are considered to represent the avoided extraction of recycled materials according to the LCA methodology [10]. There is no large-scale mature technology yet for the recycling of thermoset GFRP materials in the blades. The model assumes that 50% of it is landfilled and 50% is incinerated, a representative scenario for turbines currently decommissioned in Europe [8]. The PVC and rubber are assumed to be 100% incinerated. The electronic components and pieces made of concrete are assumed to be 100% landfilled [9, 8]. For incineration and landfilling, emissions factors are used from Ecoinvent [19].

2.5. Validation of the developed automated LCA model

The developed LCA model is validated against other studies as shown in Figure 2, matching the inputs P_r, RD, HH and the wind resource for fair comparison. The implemented model predicts similar result ranges for IOE. No systematic bias is observed.

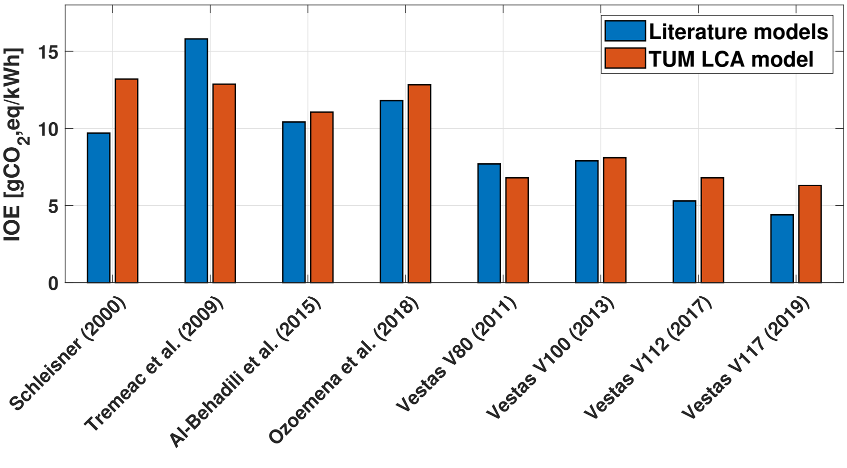

Figure 2. Result comparison of the developed LCA model with other studies [16, 20, 1, 13, 8].

3. Environmental impact of a reference wind turbine

3.1. Breakdown of the GHG emissions by life cycle stage, components and materials

The IEA Task 37 land-based reference turbine [2], with a rated power of 3.35 MW, with 130 m rotor diameter and 110 m hub height is used to illustrate the results of the LCA model (Figure 3). An average wind speed of 8.5 m/s at 110 m height is considered. The turbine is considered to be composed of raft foundations, steel shell tower, 3G-DFIG drivetrain, and conventional blades using thermoset GFRP.

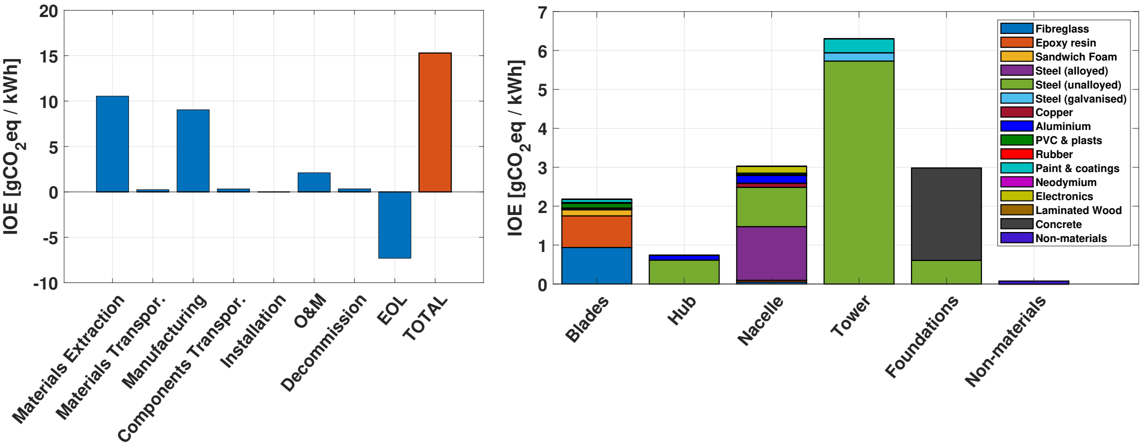

Figure 3. Breakdown of the IOE by life stages (left), and by components and materials (right) for the reference 3.35 MW turbine.

This configuration leads to an IOE of 15.29 $gCO_2eq\,/\,kWh$. The extraction of the materials and the manufacturing of components contribute the most to the environmental burden. The EOL has a negative impact due to the benefit of recycling metals. The O&M stage also corresponds to a significant environmental impact, mostly due to the replacement of failing components. Even though mostly recycled, the tower is largely the most impactful component (41%), due to the large amount of steel. The nacelle and the foundations are the two next most emitting components (about 20% each). Even though concrete is not a GHG-intensive material by mass, a very large amount is necessary. On the contrary, only a relatively small mass of alloyed steel is required for the gearbox and generator, but it is impactful due to the high GHG-intensity of the process. The blades represent 14% of the GHG emissions of the turbine. The GFRP blade manufacturing process is less GHG-intensive than steel production. But the absence of EOL revalorization (and the resulting landfilling and incineration) leads to a significant impact in the turbine life cycle.

3.2. Sensitivity analyses

Sensitivity analyses are conducted on different life cycle hypotheses from the former reference case. Best- and worst-case scenarios are selected to determine the ranges of uncertainty shown in Figure 4.

1- Emission factors: These emission factors from Ecoinvent are linked to process technology and geographical scope [19]. The best cases correspond to low emissions through modern processes. The worst cases represent aged industry and/or locations with less restrictive environmental standards.

2- Material breakdown: All of the metal components are assumed to be composed of a higher (lower) share of alloyed steel in the worst (best) case according to variation in references [13, 9, 15, 8].

3- EOL scenario: For the worst case, the blade composites are entirely incinerated and only 70% of the metal parts are recovered. In the best case, 100% of the blade composites are landfilled, and 95% of the metals is recovered [20, 9, 8].

4- Other life cycle hypotheses: The waste factors of the materials, transportation distances, installation time, lubricant consumption and failure rates of the components are increased (decreased) for the worst (best) case.

5- Wind resource: The average wind speed is varied from $7.5\,m/s$ to $10\,m/s$.

6- Turbine lifetime: The lifetime is varied from 15 years to 25 years.

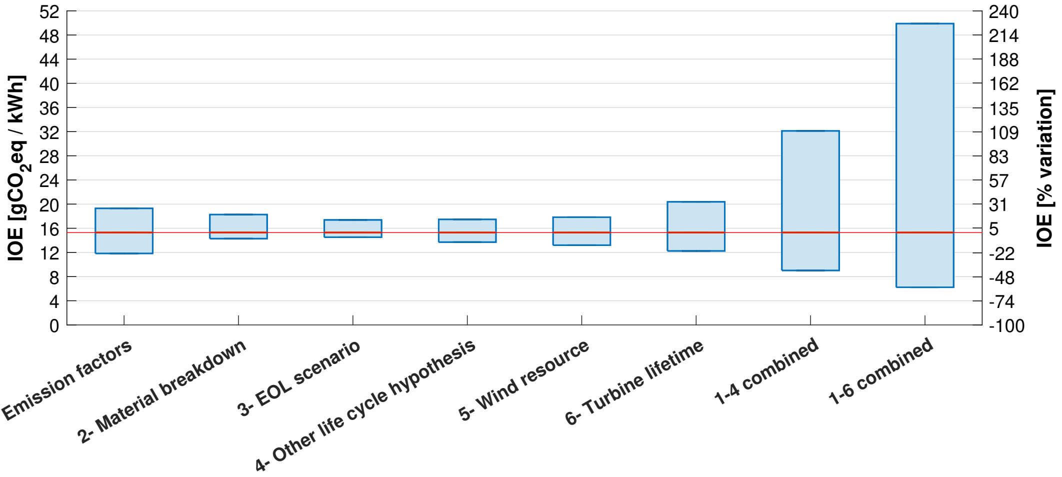

Figure 4. Sensitivity analyses (with best and worst cases considered) for different categories of hypotheses. The red line corresponds to the baseline reference case presented in Section 3.1.

The process emission factors and the turbine lifetime are likely to influence the uncertainty of IOE the most.

4. Influence of technology choices on the wind turbine environmental impact

The LCA model is applied to quantify the influence that different technology choices can have on the environmental impact. These alternative technologies are compared to the reference turbine described in Section 3.1, to analyse how the presented IOE can potentially be reduced.

4.1. Turbine size

Six configurations of P_r, RD and HH are compared on Table 2. Results indicate that, for the selected cases, the carbon footprint increases for taller towers and larger rotor diameters. The related increase in energy production is not high enough to compensate for the increase in material consumption. On the other hand, increasing the rated power appears to reduce IOE, as the AEP_net increases more than the GHG emissions.

4.2. Foundation type

Raft foundations are one of the major sources of GHG emissions due to the large amount of concrete. A possible alternative are piled-raft foundations, as defined in ref. [17]. New material masses are estimated from this source. Based on the developed LCA model, these two solutions lead to the estimations presented in Table 3. Even though the total mass is significantly decreased with piled-raft foundations, the final IOE is increased by 12.69% due to the required amount of steel, which is a more CO_2-intensive material than concrete.

Table 2. Influence of the turbine size (reference case in bold).

P_r $[MW]$	3.35	3.35	**3.35**	5	5	5
RD $[m]$	110	110	**130**	130	130	150
HH $[m]$	90	110	**110**	110	130	130
AEP $[MWh]$	8573	9052	**10334**	13153	13739	15378
Total life cycle GHG $[tCO_2eq]$	2136	2434	**3161**	3353	3780	4761
IOE $[gCO_2eq\,/\,kWh]$	12.46	13.45	**15.29**	12.75	13.75	15.48

Table 3. Influence of the foundations type (reference case in bold).

	Raft foundations	Piled-raft foundations
Foundations concrete mass $[t]$	**1276**	383
Foundations steel mass $[t]$	**53**	368
Total turbine life cycle GHG $[tCO_2eq]$	**3161**	3561
IOE $[gCO_2eq\,/\,kWh]$	**15.29**	17.23

4.3. Tower type

Several possible technology alternatives exist to the most-conventional steel shell tower. Sizing data (by hub height and rotor swept area) from ref. [6] are used to estimate material masses of alternative options. The hybrid tower is composed of a concrete lower part and a steel upper part. The wooden tower is made of laminated veneer lumber (LVL). The results in Table 4 show that adding concrete to the tower to limit the steel consumption is beneficial in terms of GHG emissions. The concrete tower reduces the overall IOE by 8.31%, and by 11.51% with the hybrid tower, which also requires less concrete. But the most environmentally friendly option appears to be the wooden tower, as it reduces the IOE by up to 27.53%.

Table 4. Influence of the tower type (reference case in bold).

	Steel shell tower	Concrete tower	Hybrid tower	Wooden tower
Tower steel mass $[t]$	**493**	164	228	
Tower concrete mass $[t]$		1563	860	
Tower wood mass $[t]$				487
Turbine life cycle GHG $[tCO_2eq]$	**3161**	2898	2795	2289
IOE $[gCO_2eq\,/\,kWh]$	**15.29**	14.02	13.53	11.08

4.4. Drivetrain technology

The choice of drivetrain technology is commonly driven by trade-offs between energy yield, reliability and costs. The LCA model is applied to quantify the effect on the GHG emissions. Using data from ref. [11], configurations with three-stage gearbox (3G), single-stage gearbox (1G) and direct-drive (DD) are assessed. The choice of gearbox type is linked to the selection among Doubly-Fed Induction Generator (DFIG), Squirrel-Cage Induction Generator (SCIG), Permanent Magnet Synchronous Generator (PMSG) and Electrically Excited Synchronous Generator (EESG). For each type, the gearbox mass, the generator mass and its material breakdown (into alloyed steel, copper and permanent magnet NdFeB), the converter mass and the overall drivetrain efficiency are sized according to ref. [11]. The results (Figure 5) show that for the drivetrain technology the trade-off is tight in terms of IOE. For example, the DD-PMSG leads to the highest energy yield, but its increased generator mass including rare-earth

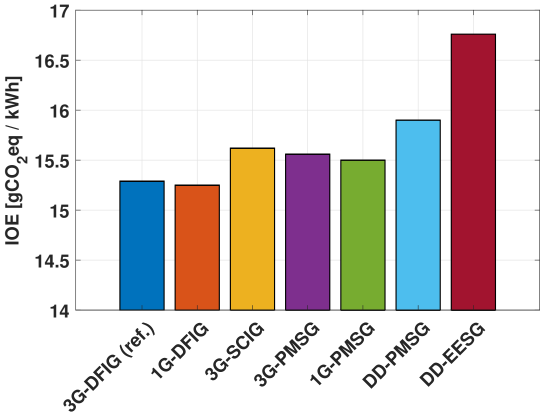

Figure 5. Influence of drivetrain type.

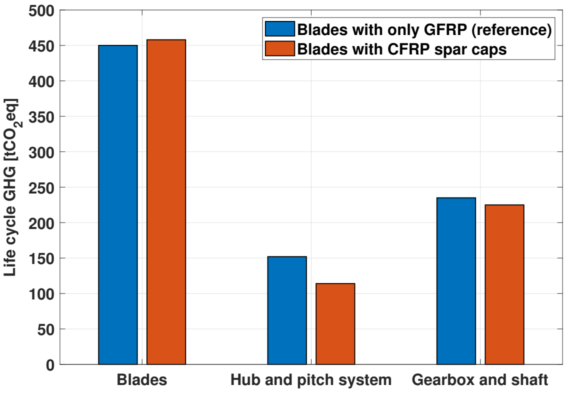

Figure 6. Influence of CFRP blade spar caps.

magnets leads to a high environmental impact. According to these estimations, only the 1G-DFIG has slightly lower IOE than the reference 3G-DFIG (-0.26%). This is due to the fact that the DFIG allows one to have a relatively smaller converter. Furthermore, the single-stage reduces the gearbox mass. On the contrary, the DD-EESG appears to be the worst configuration ($+9.61\%$ in IOE). This choice features the lowest efficiency and a very heavy generator. Overall, only small opportunities for reducing the environmental impact is expected from drivetrain type considerations.

4.5. Blades with CFRP spar caps

Carbon-Fiber Reinforced Polymer (CFRP) can be introduced in the structural part of the blades in addition to the conventional GFRP. Its high strength-to-weight ratio allows to reduce the blade mass. In turn, this enables to reduce the hub, pitch system, gearbox and shaft masses [21, 7], which are modeled from ref. [21]. The scenario where CFRP spar caps reduce the total blade mass by -27% is adopted from ref. [7], with related fibers mass distribution. The life cycle GHG of these elements are then compared in Figure 6. Even though the blade mass is strongly reduced, its life cycle GHG emissions increase due to the very high GHG-intensity of carbon fibers [19]. However, the mass reduction of the other elements results in a slight global reduction of the IOE to $15.10\, gCO_2eq\,/\,kWh$ (-1.24%). These results seem to indicate that the effect of CFRP on IOE is certainly a tight trade-off. In fact, CFRP is likely to increase the blade impact, but it can potentially have an overall slightly positive effect at the turbine level.

4.6. Blades with thermoplastics GFRP

Another possible opportunity to reduce the environmental impact of the turbine blades is the use of innovative thermoplastic resin, instead of the thermoset resin for the GFRP. The main advantage of thermoplastics is that they can potentially be recycled at the EOL, with a reheating process to decompose the fibers and the matrix for a second-life use [12, 4]. The example of the Elium thermoplastic resin is here assessed. According to [4], about 90% of the Elium resin and 50% of the fiberglass can be recovered at EOL. Furthermore, it is claimed that the Elium resin can possibly enable a significant reduction in manufacturing energy because of curing at room temperature and reduced cycle time [12]. Due to the uncertainty of these claims in the development of thermoplastics for large-scale application, different scenarios are considered:

- Elium scenario 1: same manufacturing energy, 90% of the resin and 50% of the fiberglass recovered at the EOL

- Elium scenario 2: 50% manufacturing energy, 90% of the resin and 50% of the fiberglass recovered at the EOL
- Elium scenario 3: same manufacturing energy, only 50% of the resin is recovered at the EOL (and still 50% of the fiberglass)

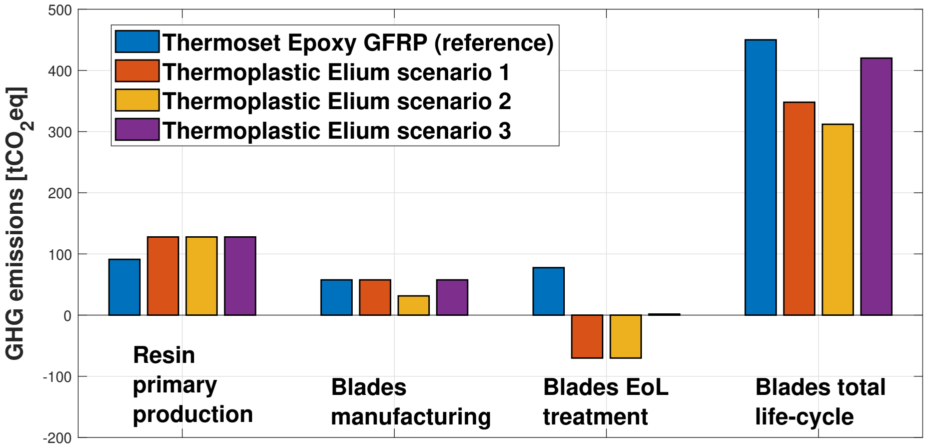

Figure 7. Results of the influence of the GFRP resin type on the environmental impact.

The LCA estimations (Figure 7) show that the use of thermoplastic could indeed significantly decrease the life cycle emissions of the blades. Even though the environmental burden of the resin production is higher, EOL recycling results to an overall reduced environmental impact for the life cycle of these components. The EOL GHG emissions of the blades are negative for the scenarios 1 and 2, meaning that the environmental credit of the material recovery overcomes the burdens of the EOL treatment (energy use for the reheating process and incineration of the non-recovered materials). At the global turbine level, the best-case scenario 2 leads to an IOE of 14.59 $gCO_2eq\,/\,kWh$ (−4.58%). With a less optimistic material recovery rate, scenario 3 is decreasing the IOE to 15.14 $gCO_2eq\,/\,kWh$ (−0.98%), compared to the conventional thermoset.

5. Conclusions

An automated wind turbine LCA model has been developed and integrated in a framework to assess the benefit of technology choices with respect to IOE. The applied method has been validated by comparison to other publications. Uncertainty ranges of the IOE have been estimated by sensitivity analyses.

The extraction of materials and the manufacturing of components are responsible for the vast majority of the wind turbine GHG emissions. In terms of components, the tower causes the most emissions, even though it is mostly recycled at the EOL. The blades also have a significant environmental impact due to their lack of recyclability at the current state of technology.

Several parametric studies have shown that wooden towers and thermoplastic polymer resin for the blades are two technology alternatives that are most likely to decrease wind turbine IOE, if they can be developed at a large-scale. As a first preliminary study to include LCA in a wind turbine design framework, some important assumptions had to be made to model the different technology alternatives. More detailed studies should be conducted next to validate the trends that were identified here. Finally, other environmental impacts than climate change should be investigated (as biodiversity impact, land use, etc.).

Recent work in our group has expanded the applicability of this LCA model to offshore wind turbines and wind farms. The model is also being used for single-objective and multi-objective design optimizations.

Acknowledgments

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