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Trend in environmental impact of the energy produced and distributed by wind power systems

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The authors declare no conflict of interest.

Abstract

Wind turbine (WT) manufacturers are focusing on reducing the cost of energy produced by new models; however, the same consideration has not been given to their environmental consequences, nor the academic literature. For these reasons, the case study focuses on the environmental performance of the energy generated and distributed by the models launched from 2010 to 2018 by a world-leading manufacturer. It has been shown that, in relation to the year of release, the impacts per kWh of electricity generated and distributed increase on annual average in the four categories of environmental impact analysed: Acidification potential, 11.3%; Eutrophication potential, 34.5%; Global warming potential, 7.8%; and Photochemical ozone, 3.2%. The "Raw material acquisition and WT manufacturing" phase accounts for 49% to 74% of the global impacts generated, depending on the model and the category analysed. This is mainly due to energy consumption in the manufacturing of blades and consumption of electrical and electronic components in cabinets and converter. In the "Construction of wind farms" phase, impacts vary between 21% and 41%. Transport, steel and concrete in the foundations and metals in the transmission network are the most critical aspects. In the "Operation and Maintenance" phase, impacts vary between 3.5% and 27%, but it is the phase with the highest growth in impact, mainly due to the replacement of larger blades. Finally, the "End of life" phase generates the lowest impact (between 0.3 and 4%). The research highlights the need to control the environmental impacts of all energy sources, including renewable energies.

Keywords

Renewable energy, Wind energy, Environmental impact, Wind turbine.

1. Introduction

Over the last decade, the improvement of wind power generation systems has greatly improved the competitiveness of wind energy with respect to other energy sources, including conventional ones (IRENA 2019). The installed wind power capacity worldwide has grown steadily and at the end of 2018 it exceeded 597 GW (GWEC 2019). Furthermore, predictions for the future appear to be optimistic, as the annual installed wind power generation capacity is expected to reach 20% of the energy demand by 2040, becoming one of the main sources of electricity generation worldwide (McKinsey 2019; Ray 2019).

Another driving force behind the spread of wind energy is that it is considered an environmentally benign source of electricity (Chiang et al. 2016) because its CO_2 emissions are comparable or lower to other Renewable Energy Systems (RES) (Singh et al. 2011) and these, together with SO_4, are its main emissions (Arvesen and Hertwich 2012). In addition, other less critical emissions compared to Green House Gas (GHG), such as NOx, SO_2, non-methane volatile organic compounds (NMVOCs) and particulate emissions also appear to occur in lower quantities than other RES, with the exception of geothermal and hydroelectric energy (Atilgan and Azapagic 2016). Conversely, other studies indicate wind power as one of the worst RES options for Human Toxicity Potential impact (Atilgan and Azapagic 2016); an aspect that tends to be considered insignificantly by other researchers (Xue et al. 2015).

However, it is worth mentioning that in recent years we have witnessed radical changes in the designs of Wind Turbines (WT). In order to capture more wind power and gain economic efficiency, the general trend among Original Equipment Manufacturers (OEMs) is to create larger-sized WTs. They make more locations viable that previously would not have been profitable, because new WTs are more effective in adapting to weather conditions. According to the survey of 163 of the world's leading wind energy experts, rotors with longer diameters and higher towers appear to be the main driving factors in reducing the Levelized Cost of Electricity (LCOE) (Wiser et al. 2016), which is an assessment of the economic lifetime energy production and cost (Leung and Yang 2012). It is precisely these design changes aimed at reducing the LCOE that influence the environmental impact of wind energy generation systems throughout their life cycle (Xue et al. 2015). However, in the literature, there is no agreement on this influence.

On the one hand, reviewing an extensive set of case studies on wind energy systems between 2000 and 2018, Mendecka and Lombardi (2019) pointed out the average trend to create higher hub WTs with longer blades. This trend is related to a decrease in environmental impact per unit of energy produced (kWh) in three main impact categories: Acidification Potential (AP), Eutrophication Potential (EP) and Global Warming Potential (GWP). Caduff et al. (2012) also concluded that the GWP impact category is lower in large WTs, though they limit the extrapolation of its model in the short term and with the same turbine technology. Similarly, Demir and Taşkın (2013) state that as the power of the WTs and the heights of the hubs increase, the quantities of the materials used in the components of the WTs also increase, but the environmental impacts per 1 kWh produced are lower for WTs due to the increase in electricity production.

On the other hand, some authors (Dolan and Heath 2012; Wang and Wang 2015) highlighted that GHG emissions, the major contributor of GWP, appear to grow with the increasing nameplate capacity trend of the WTs. This is due to strong economies of scale for power ratings up to 1 MW, although there is no clear evidence for this. In addition, an increase in size of the WTs does not necessarily imply an increase in the nameplate capacity, but it does imply an increase in the environmental impact caused mainly by an increase in necessary resources (Wang and Wang 2015).

Whatever the trend, it is essential to analyse the distribution of environmental impacts throughout the life cycle in order to understand the main sources of environmental impact and to act to reduce their effect. Arvesen and Hertwich (2012) conducted an extensive review of 44 papers on the environmental impacts of the Life Cycle Assessment (LCA) of wind energy. They concluded that the bulk emissions appear to be in the manufacturing phase. A conclusion widely corroborated in the literature by recent studies (Martínez et al. 2018; Ozoemena et al. 2018; Alsaleh and Sattler 2019). The relative contribution of this phase occasionally reaches 90%. The tower can represent 30-70% of the share on multi-megawatt WTs, mainly due to the mining of steel and concrete, which generates the highest AP, EP, and Photochemical Ozone Creation Potential (PO) impact values (Demir and Taşkın, 2013). In the manufacturing process, significant amounts of pollutants are emitted, such as SO_2, NO_x and CO_2 in the manufacturing of metal components. They are the main causes of the potential impact of acidification and phosphates, and primarily responsible for EP (Razdan and Garrett 2015), and CO_2 is the most contributing emission to GWP (Demir and Taşkın 2013). Furthermore, heavy metals like chromium, molybdenum, nickel, beryllium, cobalt, vanadium and copper emitted to the water are the main cause of the marine aquatic ecotoxicity potential. Emissions of construction materials, such as fibreglass, concrete, chromium, and steel, cause ozone layer depletion. Finally, chromium and mercury emissions are the main contributors to land ecotoxicity potential (Razdan and Garrett 2015). Some reduction in impact in this phase is also possible by using recycled materials (Atilgan and Azapagic 2016).

It is also at the manufacturing stage that energy consumption is at its highest of the whole system in the life cycle (Alsaleh and Sattler 2019). The energy used for the extraction and processing of building materials is also the main cause of the abiotic depletion potential of fossil resources (Guezuraga et al. 2012). Nevertheless, wind energy has the lowest embodied energy, according to the review of more than 100 different case studies, including solar energy (CSP, PV), wind power, hydropower and geothermal power (Asdrubali et al. 2015). Another important concentration of emissions is the transport phase, which can reach 30% of the overall impact of the life cycle (Arvesen and Hertwich 2012). Component transportation in the construction phase of the wind farm (WF) should be as limited as possible (Alsaleh and Sattler 2019), even though the impact of this phase is smaller than in the manufacturing phase (Martínez et al. 2018). The Operation and Maintenance (O&M) phase has even less impact. Authors such as Schreiber et al. (2019) state that the O&M phase is insignificant with respect to the global environmental impact. Emissions and energy consumption during the O&M phase are very low, with an average of 2% for regular routine preventive maintenance that includes: oil change, lubrication and transportation fuel consumption (Chipindula et al. 2018). However, even taking into account the performance of preventive maintenance, it is necessary to include the complete replacement of the generator or gearbox for serious failure, and the blades, which are by far the most contributing element in the corrective maintenance, given the greater probability of having to replace the blades (Liu and Barlow 2017). In any case, according to the literature, in the categories analysed (AP, EP, GWP and PO) in the worst case the impact does not exceed 7.3% of the global amount, specifically in the AP category (Schreiber et al. 2019). Regarding the End-of-Life (EoL) phase, unlike the other phases, it can positively contribute to reducing GHG emissions by around 20% due to the reuse mainly of steel and concrete (Arvesen and Hertwich, 2012).

All these values gathered in the literature are based on diverse data sources and methodologies. When different LCA methods (Ec99, RECIPE, CML 2001, IPCC…), characterisation factors, Life Cycle Inventory (LCI) methods (Process based modelling, Input-Output (IO) LCI…), databases (Ecoinvent, GaBi, Umberto libraries, CPM LCA…), system boundaries and assumptions are used to assess environmental impacts, comparisons of similar products from the same or different companies may be distorted (JRC-IEA 2010; Hauschild et al. 2013; Herrmann and Moltesen 2015). Thus, simplified LCA models and harmonization procedures are commonly used to compare the environmental impact of the energy produced and distributed by WTs (Mendecka and Lombardi 2019). Therefore, the models focus on certain life cycle impacts but do not analyse the causes of the critical points. However, it is necessary to carry out an analysis, in sufficient detail while maintaining the boundary conditions, to analyse the sources of impact that could be marking the evolution of undesirable environmental behaviour of WTs and of the energy produced. This could determine whether the wind sector is moving towards the development of more environmentally sustainable energy and identify the key environmental aspects to try to correct, if necessary, the drift in some aspects, which is not sufficiently clarified in the literature. To address this challenge, innovative research has been developed, which analyses the environmental impact trend in energy produced and distributed by the different models designed by a single OEM for the same wind conditions and using the same LCA methodology, software and inventory assumptions.

Considering this gap in the literature, the portfolio of a leading OEM manufacturer has been analysed in the period 2010-2018. The evolution of the environmental impacts of the energy produced and distributed by the WTs has been analysed in relation to the year in which they were developed. The environmental impact has been analysed in the four most relevant categories, AP, EP, GWP and PO, mentioned in the literature (Mendecka and Lombardi 2019), as well as the distribution of the values of these impact categories and the factors that produce them throughout the life cycle of the WTs. With this objective in mind, the rest of the article has been structured as follows. After this introduction, the research methodology is described. In sections 3 and 4, the results and discussion are shown. Subsequently, in section 5, the conclusions of interest to those stakeholders and academics analysing the environmental performance of RES in general and wind energy, in particular, are presented. Finally, in the last section, references used in the research are listed.

2. Methodology

The case study in this research focuses on reality. According to Yin and other reference methodological authors, the question of the generalization of qualitative studies lies in the development of a theory that can be transferred to other cases in later studies (Maxwell and Chmiel 2014; Yin 2017).

The OEM chosen for the development of the cases is one of the top five OEMs by sales volume and by cumulative installed power with more than 100 GW installed worldwide in December 2018. The company has a broad portfolio of products and divisions in Europe, America and Asia (BNEF 2018). In terms of environmental management, the OEM has a multi-centre environmental management system in line with the ISO 14001 (ISO 2015) reference standard, covering almost 100% of its production capacity worldwide and setting the goal of achieving carbon neutrality by 2025. Also, the company annually verifies GHG emissions according to the ISO 14064 series (ISO 2006d) and develops environmental product declarations for several multi-megawatt models in its catalogue, based on ISO 14025 (ISO 2006a) and CEN 15804:2012+A1 (CEN 2013).

The analysis was based on the LCA of the seven reference models of each new WT design launched on the market from 2010-2018. The models chosen were selected for being the flagship references in the OEM's catalogue, in terms of sales volume, product diversification, geographical expansion and degree of environmental performance at corporate level. The LCAs were made according to ISO 14040:2006 (ISO 2006b) and 14044:2006 (ISO2006c) environmental management standards (ISO 2006). This methodology is widely used in the field of environmental product performance evaluation of WTs (Guezuraga et al. 2012; Demir and Taşkın 2013; Bonou et al. 2016; Ozoemena 2016). However, LCA used as a tool to assess sustainability is not without its limitations (Turconi et al. 2013; Asdrubali et al. 2015). The most critical methodological aspects related to LCA studies were identified as the definition of the functional unit, the emission allocation principle, system boundary expansion, and the assessment method employed. It is the responsibility of the analyst to ensure that all necessary inputs and outputs are properly considered (Hertwich et al. 2015).

In our research, the LCA methodology includes all the manufacturing processes (see Fig.1) carried out by the OEM and nearly 5,000 suppliers. The main life cycle phases of WTs are:

- Raw materials and WT manufacturing (logistic activities are considered).
- WF construction (including the infrastructure required for the electrical transmission and distribution of the generated electricity to the customer).
- Operation and maintenance.
- EoL (adding the impact of the decommissioning and EoL treatment of all the parts involved).

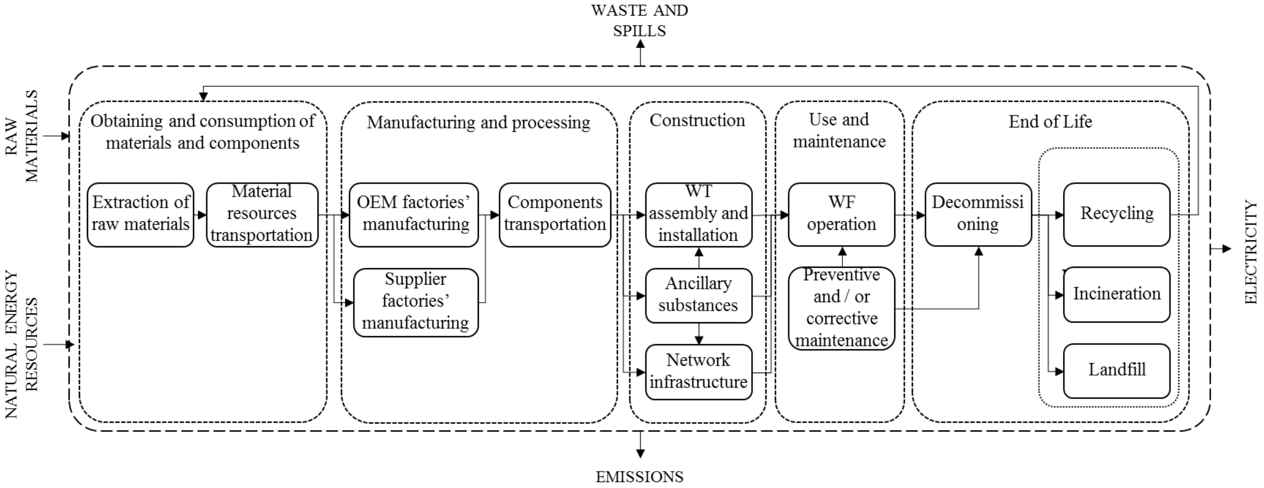
To measure environmental impacts, we have focused on the midpoint oriented impact categories: AP, EP, GWP, and PO, as they are the most relevant and commonly used in the literature. In addition, impacts at the midpoint level are quite accurately modelled and are in line with recent energy and environmental policies, according to Mendecka and Lombardi (2019).

In addition to our study, environmental aspects such as noise or light pollution, electromagnetic interference, visual impacts and impacts on wildlife have not been taken into account. Such impacts are beyond the scope of an LCA. They are not induced by substances, nor are they directly related to emissions and physical exchanges of materials with the environment, however, they do cause alterations in the environment. Although methodological attempts have been made, the process of modelling the associated impacts is not sufficiently developed (Landeta et al. 2018).

On the other hand, given the complexity of the Life Cycle Inventory (LCI) of a WT and a WF, it is difficult to gather 100% of real data and it can be over or underestimated. The objective in this study was to include at least 98% of the total mass and energy inputs in the life cycle of each WT model. We have excluded material flows that total less than 1% in weight of the total of all material flows as well as energy flows that are less than 1% of all energy flows.

In order to compare the environmental sustainability of the life of the product manufactured by the OEM, the evolution of the environmental impacts of the last seven main reference models have been analysed (each one coded with a number that depends on their launch year and their power capacity, as can be seen in Table 1). The process was conducted by identifying, calculating and evaluating the potential environmental impact in all cases, the same LCIA, software assessment tool and selected impact categories have been maintained. Ecoinvent database (3.0 version) for LCI, CML-IA (baseline, 4.8 version) method for LCIA and SimaPro (8.0 version) software were applied. When available, primary data was collected from the OEM and its suppliers from different sources. When primary data was not available, other secondary sources were consulted, such as Ecoinvent database for production of primary materials, electrical grid infrastructure, means of transport emissions, or end of life treatments and Red Eléctrica Española for electricity mix (see Figure 1).

Fig. 1: Simplified representation of the boundaries of the studied system.



The direct comparison of environmental impacts is often distorted by taking different assumptions as a reference (Greening and Azapagic 2013). Bonou et al. (2016) highlight the uncertainty of the last two phases due to the expected technological improvements. For these reasons, this research has maintained the objective, scope and other assumptions as far as possible. Efforts have also been made to avoid assumptions that lead to an overestimation of the impacts affecting the interpretation of the results. Among these assumptions, the following should be noted:

- Geographical location: The selection of the site where the OEM cases will be conducted is a central element, as a simple analysis unit is required to be representative within the industry (Yin 2017). Spain has been chosen for the location of the wind farm because it accounts for more than half of the installed capacity of the OEM in Europe. Additionally, a sensitivity analysis carried out for the W2010 model compared the main wind farm locations with the highest installed capacity by the OEM (more than 85% of the total in Europe) and found that the impacts that differed most from the average were in Poland and Italy. The AP category in these countries showed impacts 3.1% and 2.2% higher, respectively, and in both cases, 1.7% higher in the EP category. In the rest of the impact categories analysed, the variation was no more than 1%.
- Wind conditions: All outcomes of environmental performance referred to 1 kWh of electricity generated below medium wind conditions (class IIA, according to the International Electrotechnical Commission) and distributed through an onshore WF. Electricity generated is then distributed to a consumer connected to a 132 kV grid, 15km away. According to the European sectoral association Eurelectric, the value of electrical losses through transmission and distribution amounts to 6.6% of the total annual energy generated, and it is estimated that they will remain practically constant until 2020 (CEER 2017).
- Dimension of the WF: The size of each WF has the average requirement of materials and civil works for each WT installed. As a result, the environmental impact of the construction of the WF refers to each turbine installed and is not limited to a particular farm size. Common infrastructure values have always been assigned in the same proportion, taking on average a 28.5MW wind farm installed by the OEM in Europe.
- Availability of operation and useful life: An average WT has an availability of 98% with a 20-year lifespan. However, the analysis shows the useful life of WT's is extending, which is increasing the necessary maintenance operations.
- The recycling level is estimated at 98% for metals (whether ferrous or non-ferrous), 99% for cables, 90% for plastics and 50% for electrical/electronic components. Lubricants, greases and oils are estimated to be fully incinerated. The carbon and fibreglass sent to landfill and the paints and adhesives are not recycled either.

The present study has not been limited to the static analysis of the LCA of each WT per 1 kWh of electricity generated and distributed. The trends in the environmental impacts of the successive WTs launched on the market by the OEM have been measured. In the analysis, boundary conditions have been maintained and the same assumptions have been considered to minimize inconsistent results in both quantity and quality.

In order to analyse the trend in each environmental impact (AP, EP, GWP, and PO), linear functions have been calculated using the software SPSS statistics 26. In the linear regression analysis, the prediction of the different impact categories with regard to the launch year has been estimated, where 2010 is the *year 0*. The following equation has been calculated using maximum likelihood estimation:

$$\textit{Environmental impact (AP, EP, GWP, and PO)} = \textit{Constant} + \beta * \textit{(Launch year-2010)} \qquad (1)$$

The parameters are calculated to minimize the sum of mean squared loss (Harrell 2015). The regression function is defined by the constant (Const.) and the β coefficient representing the influence of the launch year on the environmental impact of the energy produced and distributed by each model. If β is positive and significant, the environmental impact for that category of the energy produced and distributed by the newer models tends to be greater. Using the β coefficient and the value of the constant, the annual variation (Var.) with regard to the constant in 2010 (year 0) has been measured to give a relative indicator of the evolution (β/Cons.) (Harrell 2015). In this respect, *F – tests* have been carried out to calculate the F and α values to measure the significance of the regressions. R^2 explains the variance of the dependent variable (Harrel 2015). The Pearson correlation test (Cor.) has been measured using SPSS statistics 26 (Weisberg 2005).

3. Results

3.1 Main characteristics of the WTs

From 2010-2018, the OEM worked on the design, manufacturing and installation of seven WT models IEC Wind class IIA. The W2010 was the first launched on the market in 2010. It accumulates about 22 GW installed capacity in 37 countries and represents 60% of the total MW installed by the OEM until the end of 2018. In 2012, the W2012 was the second, showing increases of 38% of the swept area. In 2015, the OEM presented the W2515 and W5015 models. The W2515 was based on the W2012 but its power was increased by 0.5 MW. The W5015 was the first multi-megawatt platform model with 5MW nameplate capacity. A year later, the fifth WT model was launched, the W5016; this model generates 3% more energy than the W5015 because it is more efficient. The sixth model, W3317, has the lowest estimated LCOE. Finally, the OEM product catalogue was completed at the end of the analysis period with the W2618. The last two models are the most flexible for working in a larger range of wind conditions.

In Table 1, the trend in the main characteristics: rotor diameter, swept area, blade length, tower height, and nominal power of the WTs designed by the OEM can be observed. The WTs tend to be larger. In fact, the rotor diameter, the swept area and the length of the blades have increased (significant annual variations -1.2%, -10.9% and -4.8%), in order to capture more wind and reduce the cost of energy generation.

Table 1: Main characteristics of the WTs.

Model	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β.	Var.	F	R^2	Cor.
Year	2010	2012	2015	2015	2016	2017	2018						
Rotor diameter (m)	90	114	114	128	132	132	126	97.476	1.178	0.012	15.617**	0.757	0.870**
Swept area (m^2)	6,362	10,207	10,207	12,868	13,685	13,685	12,469	7,504	817	0.109	15.346**	0.754	0.,868**
Blade length (m)	44	56	56	62.5	64.5	64.5	62	47.715	2.288	0.048	16.594***	0.768	0.877***
Tower height (m)	78	80	88	140	140	114	84	83.861	4.151	0.049	1.081	0.178	0.422
Nominal Power (MW)	2	2	2.5	5	5	3.465	2.625	2.207	0.216	0.098	1.382	0.217	0.465
IEC Wind class	IIA	IIA	IIA	IIA	IIA	IIA	IIA						

3.2 Use of natural resources

Table 2 shows, on the one hand, the reduction in non-renewable material consumption per kWh produced and distributed of Gravel, Iron, Clay, and Nickel (significant annual variations -10.4%, -4.1%, -8.3% and -9.5%) and in recycled material resources consumption of Copper (significant annual variation -16.7%). On the other hand, there is an important increase in Aluminium (significant annual variation 90%). This is due to the OEM's effort to use more recycled material resources and to reduce the use of non-renewable material resources.

Table 2: Main material resources used per kWh electricity generated and distributed related to the launch year.

Non-renewable material resources (g)	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β	Var.	F	R^2	Cor.
Gravel	36.8	29.9	5.7	26.8	21.1	6.1	6.05	37.251	-3.888	-0.104	12.158**	0.709	-0,842**
Iron	2.33	1.57	1.53	1.65	1.71	1.55	1.40	2.074	-0.084	-0.041	7.738**	0.607	-0,779**
Calcite	1.69	1.42	1.47	1.96	1.58	1.27	1.25	1.619	-0.038	-0.023	1.117	0.183	-0,427
Clay	0.648	0.631	0.410	0.611	0.450	0.160	0.191	0.732	-0.061	-0.083	12.260**	0.710	-0,843**
Sodium chloride	0.189	0.326	0.175	0.142	0.161	0.183	0.204	0.236	-0.008	-0.034	0.863	0.147	-0,384
Nickel	0.186	0.189	0.071	0.066	0.070	0.079	0.063	0.190	-0.018	-0.095	20.781***	0.806	-0,898***
Other non-renewable	0.210	0.144	0.099	0.216	0.210	0.071	0.083	0.206	-0.012	-0.058	2.051	0.291	-0,539
Recycled material resources (g)													
Aluminium	0.0101	0.0098	0.0531	0.0478	0.050	0.0342	0.054	0.010	0.009	0,900	11.088**	0.689	0,830**
Copper	0.0069	0.0050	0.0038	0.0017	0.002	0.0026	0.0037	0.006	-0.001	-0,167	7.469**	0.599	-0,774**
Steel	0.9161	0.6570	0.7196	0.6600	0.6600	0.7607	0.681	0.810	-0.019	-0,023	2.262	0.312	-0,558

Note: *Significant for α=0.1. **Significant for α=0.05. ***Significant for α=0.01.

3.3 Waste generated

The waste produced by WTs is one of the most important environmental impacts of their life cycle. Table 3 shows the waste generated per kWh of energy produced and distributed and the trend according to the WT's year of design. As can be seen, in the first two WTs the Hazardous Non-Radioactive Waste generated was not recyclable, however, since 2015 the models have started using and generating less non-recyclable waste (significant annual variation -9.43%).

Radiology remains very low due to the lack of radioactive elements. However, the final volume required for Hazardous Low-Radioactive Waste is being increased in the new models (significant annual variation 19.7%). In contrast, more radioactive elements are decreasing (significant annual variation -10.7%).

Regarding the other waste, the most remarkable aspect is related to the treatment of the waste because the OEM is minimizing the waste for incineration (significant annual variation -14.8%) and increasing the proportion for recycling purposes (significant annual variation –6.0%).

Table 3: Main waste generated per kWh of electricity generated and distributed related to the launch year.

Hazardous non-radioact. waste (g)	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β	Var.	F	R^2	Cor.
Non-recyclable	5.99E-02	5.41E-02	1.50E-02	5.53E-02	2.94E-02	1.57E-02	1.62E-02	6.31E-02	-5.95E-03	-9.43E-02	9.600**	0.658	-0.811**
To recycling	0.00E+00	0.00E+00	6.38E-03	2.48E-02	2.40E-02	4.67E-03	6.65E-03	2.31E-03	1.52E-03	6.58E-01	0.991	0.165	0.407
Hazardous radioactive waste (m^3)													
Vol. final repository	1.87E-11	1.71E-11	5.13E-12	6.83E-12	5.77E-12	5.33E-12	5.37E-12	1.85E-11	-1.98E-12	-1.07E-01	30.673***	0.860	0.927***
Vol. final repository low active	7.47E-11	6.85E-11	1.70E-10	1.88E-10	1.54E-10	1.54E-10	1.72E-10	7.26E-11	1.43E-11	1.97E-01	11.406**	0.695	0.834**
Other waste (g)													
Non-hazardous to landfill	8.58E+00	7.21E+00	4.47E+00	1.15E+01	7.69E+00	4.71E+00	4.49E+00	8.94E+00	-0.42E-01	-4.70E-03	1.295	0.206	-0.454
Non-hazardous to incineration	1.69E-01	2.18E-01	0.00E+00	1.03E-02	1.05E-02	0.00E+00	0.00E+00	1.95E-01	-2.89E-02	-1.48E-01	15.435**	0.755	-0.869**
Non-hazardous to recycling	2.60E+00	2.43E+00	1.51E+00	1.45E+00	1.77E+00	1.65E+00	1.41E+00	2.56E+00	-1.54E-01	-6.02E-02	20.204***	0.802	-0.895***

Note: *Significant for $\alpha=0.1$. **Significant for $\alpha=0.05$. ***Significant for $\alpha=0.01$.

3.4 Pollutant emissions

As can be seen in Table 4, the trend in emissions to the air of hazardous non-radioactive waste of Ammonia are only significant for $\alpha=0.01$, and it has a negative variation coefficient of -8.3%, and for Nitrogen oxides the coefficient is 5.1% ($\alpha=0.05$). The rest of the coefficients are not significant for $\alpha=0.05$.

Table 4: Emissions to the air of hazardous non-radioactive waste per kWh of electricity generated and distributed related to the launch year.

Emission to air (g)	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β	Var.	F	R^2	Cor.
Carbon diox. fossil	9.22E+00	8.41E+00	8.32E+00	9.69E+00	8.64E+00	8.09E+00	8.57E+00	7.14E+00	-8.23E-02	-0.012	0.743	0.129	-0.360
Methane fossil	2.32E-02	2.23E-02	2.39E-02	2.79E-02	2.69E-02	2.53E-02	2.61E-02	2.28E-02	4.86E-04	0.021	4.071*	0.449	0.670*
Carbon monox. fossil	7.10E-02	6.19E-02	6.03E-02	6.56E-02	6.59E-02	6.17E-02	5.97E-02	6.82E-02	-9.45E-04	-0.014	3.916	0.439	-0.663
Sulphur dioxide	4.32E-02	4.78E-02	3.45E-02	4.33E-02	4.10E-02	3.00E-02	3.21E-02	4.72E-02	-1.78E-03	-0.038	6.475*	0.564	-0.751*
Nitrogen oxides	2.93E-02	2.88E-02	4.15E-02	3.55E-02	3.20E-02	3.70E-02	4.18E-02	2.83E-02	1.45E-03	0.051	6.839**	0.578	0.760**
Ammonia	1.22E-03	1.13E-03	5.17E-04	5.60E-04	5.30E-04	5.46E-04	5.58E-04	1.20E-03	-1.00E-04	-0.083	23.265***	0.823	-0.907***
Hydrogen chloride	5.36E-04	5.46E-04	5.95E-04	7.63E-04	7.40E-04	5.99E-04	6.10E-04	5.57E-04	1.48E-05	0.027	1.384	0.217	0.466
Ethene	6.74E-05	1.88E-04	2.22E-05	3.18E-04	2.83E-04	1.96E-05	2.08E-05	1.57E-04	5.32E-06	0.034	0.068	0.013	-0.116
Pentane	1.01E-04	9.25E-05	9.53E-05	1.06E-04	8.62E-05	9.08E-05	1.02E-04	9.78E-05	-3.47E-07	-0.004	0.195	0.019	-0.137
Butane	7.47E-05	1.07E-04	7.53E-05	8.70E-05	6.87E-05	7.18E-05	8.15E-05	8.84E-05	-1.60E-06	-0.018	0.677	0.119	-0.345

Notes: Emissions contributing by more than 0.5% in any of the four potential environmental impacts assessed for the global impact of the six models. The IEA criteria (IEA. 2013) have been taken into account for the calculation of indirect emissions from electricity consumption, incorporating different conversion factors depending on the country of origin of the electricity. **Significant regression for $\alpha=0.05$. ***Significant regression for $\alpha=0.01$.

Table 5 shows the trend in the most important emissions of radioactive isotopes and other toxic substances per kWh of electricity generated and distributed. The emissions of radioactive isotopes C-14 and Rn-222 have a negative trend (significant annual variation -6.3% and -10.7%), and the Kr-85 has a positive value of annual variation 17.7%. The emissions of toxic substances appear to have reduced in the cases of Arsenic, Cadmium, as well as in the case of toxic particulates smaller than 2.5 µm. and larger than 10 µum (significant annual variation -10.4%, -10.5%, -1.9% and -5%).

Table 5: Emissions of radioactive and other toxic substances to the air per kWh of electricity generated and distributed related to the launch year.

Radioactive isotope (KBq)	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β	Var.	F	R^2	Cor.
C-14	6.50E-05	5.49E-05	3.62E-05	4.46E-05	3.61E-05	3.38E-05	3.67E-05	6.26E-05	-3.96E-06	-0.063	39.395***	0.887	-0.942***
Rn-222	1.18E+00	1.00E+00	4.53E-01	5.93E-01	5.06E-01	2.78E-01	2.86E-01	1.20E+00	-1.29E-01	-0.108	115.77***	0.956	-0.979***
Kr-85	2.00E-05	1.60E-05	4.00E-05	3.10E-05	4.70E-05	3.60E-05	3.76E-05	1.77E-05	3.14E-06	0.177	8.697**	0.635	0.797**
Emissions of biogenic carbon dioxide and toxic substances (g)													
Carbon dioxide. biogenic	2.91E-01	4.53E-01	2.28E-01	1.67E-01	1.54E-01	2.39E-01	2.70E-01	3.43E-01	-1.80E-02	-0.052	1.755	0.260	-0.510
PAH.polycyclic aromatic hydrocarbons	6.24E-06	5.61E-06	5.32E-06	6.80E-06	6.64E-06	5.08E-06	5.92E-06	6.10E-06	-3.33E-08	-0.005	0.105	0.021	-0.144
Arsenic	4.04E-05	5.11E-05	1.41E-05	1.70E-05	1.64E-05	1.17E-05	1.38E-05	4.60E-05	-4.78E-06	-0.104	14.526**	0.744	-0.863**
Cadmium	1.34E-05	1.69E-05	4.63E-06	5.70E-06	5.45E-06	3.77E-06	4.53E-06	1.53E-05	-1.59E-06	-0.105	14.823**	0.748	-0.865**
Part.<2.5 µm	8.80E-03	8.45E-03	7.95E-03	7.80E-03	7.78E-03	7.57E-03	9.52E-03	8.76E-03	-1.67E-04	-0.019	235.13***	0.979	-0.990***
Part. >10 µm	1.51E-02	1.17E-02	1.21E-02	4.78E-02	4.45E-02	1.26E-02	1.20E-02	1.83E-02	8.35E-04	0.046	0.105	0.021	0.143
Part.>2.5 µm. -<10µm	1.22E-02	1.02E-02	7.30E-03	8.24E-03	8.31E-03	7.92E-03	7.48E-03	1.20E-02	-5.78-04	-0.050	26.236***	0.840	-0.916***

Notes: Emissions contributing by more than 0.5% in any of the four potential environmental impacts assessed for the global impact of the six models. The IEA criteria (IEA. 2013) have been taken into account for the calculation of indirect emissions from electricity consumption, incorporating different conversion factors depending on the country of origin of the electricity. **Significant regression for $\alpha=0.05$. ***Significant regression for $\alpha=0.01$.

In Table 6 the emissions in water are analysed. Phosphate is the only element with a significant positive trend. In this case, the variation coefficient is very high 108.1%. The rest of the emissions in water, such as Nitrates, Chemical Oxygen Demand, Polycyclic Aromatic Hydrocarbons and oils do not have significant variations.

Table 6: Emissions to water or soil per kWh of electricity generated and distributed related to the launch year.

Emission (g)	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β	Var.	F	R^2	Cor.
Phosphate	1.76E-03	5.16E-03	2.01E-02	2.06E-02	2.06E-02	2.18E-02	2.04E-02	2.59E-03	2.80E-03	1.081	30.442***	0.859	0.927***
COD. Chem. Oxy. Dem	3.72E-02	9.27E-02	6.29E-02	3.28E-02	3.16E-02	5.51E-02	6.57E-02	5.57E-02	-3.63E-03	-0.065	0.011	0.002	-0.046
Nitrate	6.59E-04	6.55E-03	7.46E-03	6.48E-03	6.23E-03	5.53E-03	6.05E-03	3.21E-03	4.98E-04	0.155	3.202	0.390	0.625
PAH. polycyclic aromatic hydrocarbons	1.20E-06	9.02E-07	1.10E-06	9.56E-07	1.06E-06	1.16E-06	1.04E-06	1.68E-06	-1.82E-09	-0.001	0.012	0.002	-0.048
Oils. unspecified to water	3.00E-03	2.76E-03	3.13E-03	3.45E-03	2.78E-03	2.91E-03	3.32E-03	2.91E-03	2.91E-05	0.010	0.531	0.096	0.310
Oils. unspecified to soil	2.96E-03	2.72E-03	3.21E-03	3.38E-03	2.76E-03	3.02E-03	3.45E-03	2.84E-03	4.92E-05	0.017	1.516	0.233	0.482

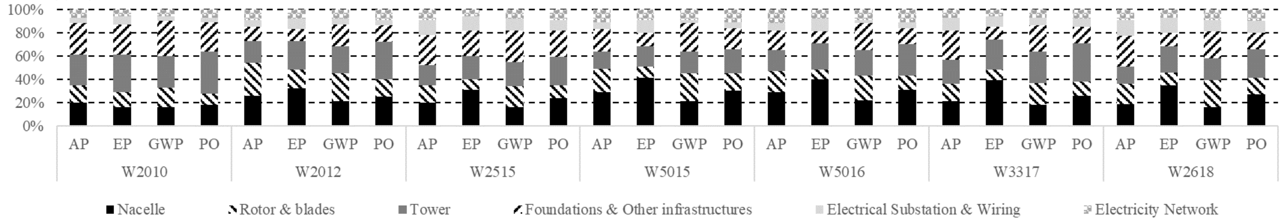
Note: Emissions contributing by more than 0.5% in any of the potential environmental impacts assessed ***Significant regression for α=0.01.

3.5 Eco profile trend

Figure 2 shows the relative importance in the four impact categories analysed (PO, GWP, EP and AP) for the main wind turbine subsystems: nacelle, rotor, tower, foundation and other infrastructures, electrical substation and electricity network. From an environmental point of view, tower and foundations are the most critical functional systems within the wind farm. They are designed to withstand and transmit the stress generated by nacelle, rotor and blades, which is directly related to the inherent weight of these functional systems.

These are the sources of the global environmental impact of the WTs, which is increasing in a significant and positive way in all four categories: PO with an average annual variation coefficient of 3.2% (α=0.05), GWP 7.8% (α=0.05), EP 34.5% (α=0.01), and AP 11.3% (α=0.05). The correlation values between the launch year and each environmental impact category are significant and greater than 0.77, as can be seen in Figure 3.

Fig. 2: Relative contribution of each subsystem (%) to the overall AP, EP, GWP and PO impact per 1 kWh of energy generated and distributed.



The environmental impact of all WT models and for all categories is mainly concentrated in the first two phases, see Figure 3. In the first phase, obtaining raw materials and WT manufacturing activities generated impacts that vary from 49%-74%. There is only one significant regression for α=0.01 in the category of EP with a positive trend and variation coefficients of 29.5%. Among all of the main categories analysed, blade manufacturing is a critical environmental aspect.

For the oldest models, W2010 and W2012, the most significant environmental aspects are fibreglass, epoxy resins, and low alloyed steel consumption. In the case of the newest WTs, W2515, W5015, W5016, W3317 and W2618 models, the most significant environmental aspects are electrical and electronic component consumption in the cabinets and the converter, and electricity and natural gas consumption during blade manufacturing. In all WTs analysed, heavyweight steel parts of the housing and insulation material consumption on the high voltage switchgears are critical aspects.

The second phase, WF construction, includes the construction processes and associated logistics of the WFs. In this phase, the concentration of the environmental impact varies by 21%-41% with significant regressions and positive variation coefficients for the AP (25% and α=0.01), EP (41.6% and α=0.01) and GWP (8.8 % and α=0.01). The tower is undoubtedly the most critical component. Depending on the customer's needs, different tower heights can be mounted to the same WT. In our research, the most common tower height of each model has been compared. The choice of the tower is always considered when trying to achieve the optimal Annual Energy Production for the specific emplacement.

The most significant environmental aspects, for all the WT models, are: the transport of materials by road or sea, the steel and concrete used in the foundations, the copper, low-alloyed steel, the metals (aluminium, copper, lead, low-alloyed steel) used in the transmission network, the oil used in the transformer substation and the fuel burned by construction machinery. Also significant are the ancillary construction materials for the W2010 and the W2012, as well as paint consumption for the W2515 model.

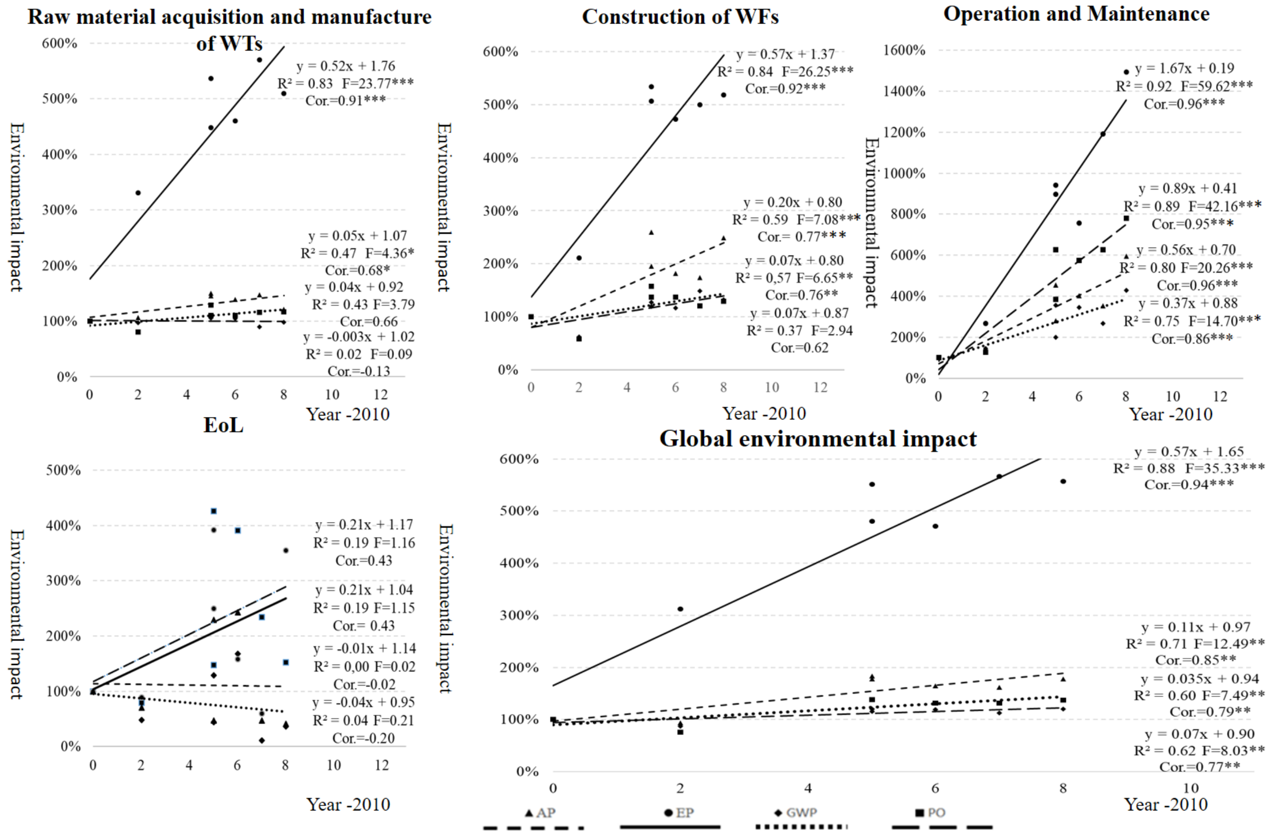
The participation of the overall environmental impact of the third phase, the operation and maintenance of the WTs and WFs, is less than 5% for all categories in the oldest WT, the W2010, and more than 9% in the newest one, the W2618. It has a significant positive trend in the proportion of the environmental impact generated in the four categories. AP (80% and α=0.01), EP (879% and α=0.01), GWC (42% and α=0.01) and PO (217% and α=0.01).

Given the need for blade replacement, blades are by far the most contributing element to the environmental impact. The manufacturing of components for replacement in the drive train and the generator also produces important impacts. The impact generated in the EoL phase varies from 0.3%-4.0%. In this case, there is no clear linear trend in any category and the main impact is related to the energy consumption produced at the EoL of the blades, especially for the WT2012 and the WT5015, due to the difficulty in recovering the valuable materials.

In some cases, it may be feasible to extend the life of WTs and the overall environmental impact of WTs may even be reduced. In fact, the OEM offers a program of audits and preventive and corrective maintenance in order to improve the reliability of the WTs and extend their life. In order to assess the influence of the extension of the useful life on the environmental impact generated by a WT, a sensitivity analysis was carried out for the W2010 model, with two scenarios:

an extension of useful life from 20-25 and from 20-30 years. The main variations of the analysis were related to energy production, additional maintenance, supplies, trips for WF maintenance personnel, EoL management of supplies and to transport them to the site, among others. The results show that the life is extended up to 5 years, producing a significant decrease in all categories of impact, with annual decrease of 20% for the AP, 22.6% for the EP, 21.3% for the GWP and 18.7% for the PO. For an extension of 10 years, the decreases are more significant with variations in all the categories from 32%-34%.

Fig. 3: Global and per phase environmental trend in the AP, EP, GWP and PO related to the launch year



Note 1: The units used are PO - C_2H_4 eq., GWP-(100a)-CO_2 eq., EP - PO_4 eq., AP - SO_2 eq.

Note 2: The unit of the x-axis is the year elapsed with respect to the base year, year-2010 (value 0). The unit of the y-axis is the relative growth in percent (%) of the impact category (PO, GWP, EP and AP) with respect to the value of the WT model in the base year, year-2010.

Note 3: *Significant regression for α=0.1. **Significant regression for α=0.05. ***Significant regression for α=0.01.

Analysing these results and taking into account the research that linked the increase of GWP with the nameplate capacity of WTs (Wang and Wang 2015) showed a regression and correlation analysis of these categories using the nameplate capacity as the independent variable, see Table 6. The variation coefficients are positive but there is no significant test in any category.

Table 7: Main environmental results obtained per kWh of electricity generated and distributed related to the nameplate capacity of each model.

Medium impact category	W2010	W2012	W2515	W5015	W5016	W3317	W2618	Const.	β	Var.	F	R^2	Cor.
PO (gC_2H_4 eq)	0.0029	0.0022	0.0040	0.0040	0.0038	0.0038	0.0398	0.0144	-0.0002	0.014	0.150	0.029	-0.171
GWP (100a) (gCO_2 eq)	8.0300	6.9700	9.2500	9.6500	9.5800	9.0500	9.6200	72.2785	0.5159	0.007	3.944	0.441	0.664
EP (gPO_4 eq)	0.0051	0.0159	0.0281	0.0245	0.0240	0.0289	0.0284	0.0133	0.0003	0.023	1.028	0.171	0.413
AP (gSO_2 eq)	0.0358	0.0334	0.0657	0.0637	0.0590	0.0579	0.0635	0.0355	0.0006	0.017	2.250	0.310	0.557

4. Discussion

It has been shown that the new models tend to produce and distribute energy with a greater environmental impact. Focusing on the life cycle of WTs, over 85% of environmental impact is concentrated in the first two phases of the life cycle: "Raw material acquisition and manufacture of WTs", and "Construction of WFs". The "Raw material acquisition and wind turbine manufacturing" phase accounts between 49% and 74% of the impact in the four categories and seven designs. The consumption of electrical and electronic components in the cabinets and converter, and the consumption of electricity and natural gas during the manufacture of the blades are critical sources. The reduction of the raw materials used has a very significant impact on all manufacturing and logistics activities. This could also facilitate the construction phase of the WF, as less weight would have to be lifted by cranes on site. The "Wind farm construction" phase causes between 21% and 41% of the impact in the four categories. The most polluting elements are transport, steel and concrete in the foundations, metals in the transmission network, transformer oil and burnt fuel. The "Operation and Maintenance" phase has the fastest growing impacts, they range from 3.5% to 27%. The replacement of the increasingly large blades is the most critical element. Finally, in the EoL phase, the environmental impact generated is low, largely because the recyclability of the machines is over 90%, the values vary between 0.3% and 4.0%. The recyclability of the blades is still a problem today, even without significant improvements.

The environmental performance of WTs can be substantially improved by prolonging their life span. This results in a significant decrease in the overall environmental impacts in all categories due to the higher energy generated by each WT, even when maintenance operations must be carried out to ensure the integrity of the machine, its features and operations, thus increasing the impact of the "Operation and Maintenance of WTs and WFs" phase. Nevertheless, the calculations made have not considered the degradation in performance over time of the WFs because there is not enough experience in this regard.

5. Conclusion

The environmental impacts of RESs are usually lower than those of conventional energy sources, but they should also be taken into account because they do generate some impacts and they are expected to grow well above conventional energy sources in the near future. However, as far as wind power generation systems are concerned, OEMs are focusing their efforts on reducing the LCOE of WTs, and in some cases the environmental impacts caused by WTs may be increasing. The literature has not paid sufficient attention to this. Some research works address the development of predictive models of the environmental impact of wind energy and, more specifically, of WT models, based on certain assumptions. They are based on simplified LCA models, they usually focus on few impact categories and do not provide sufficient detail to try to determine the origin or cause of the variation in impacts and thus obtain the precise information to be able to act and try to reduce them.

The environmental impact of the energy generated and distributed by the seven models of WTs launched from 2010 to 2018 by a leading world OEM has been analysed using the same database, method, LCIA and software assessment tool. In that period, the company carried out several strategies in its activities to reduce the environmental impact of WTs but, considering that their priority was to reduce the LCOE and improve the capacity ratio of WTs, the company did not sufficiently prioritize the mechanisms for reducing environmental impacts. Therefore, it could not adequately control the environmental performance of its WTs. The rotor and blades of new WT models tend to be larger, in line with market trends, but as demonstrated, these are precisely the two critical factors that increase the environmental impact of WTs per kWh produced and distributed to the grid

In relation to the launch year, it has been detected that the trends in environmental impacts per kWh of electricity generated and distributed have positive slopes from 2010 to 2018 in the categories of AP, EP, GWP and PO, with average annual increases of 11.3%, 34.5%, 7.8% and 3.2%, respectively. In this regard, the influence of the nameplate capacity of models on increasing environmental impact has not been confirmed. The new models tend to produce and distribute energy with greater environmental impacts. These are mainly generated in the first two phases of the life cycle; 49%-74% of these environmental impacts are produced in the "Raw material acquisition and manufacture of WTs" phase and 21%-41% in the second, "Construction of WFs". In the third phase, the impacts of the “Operation and Maintenance" increase sharply for the newer models and the average annual increase varies from 42% for PO to 879% for EP, although they represent a lower overall impact than the first two phases of the life cycle, between 3.5% and 27%. The impacts generated in the EoL phase are lower than 4%.

The conclusions of this research are based on the analysis of the environmental impacts of WT models that have been launched on the market by a leading OEM. Therefore, the main limitations of this research are related to the generalization of the results obtained to the whole wind energy sector. It would be interesting to extend the study to other OEMs with a relevant presence in the market and, this way, the OEMs could reverse some negative trends observed, and design more effective and efficient measures to reduce the environmental impact of their WTs.

Finally, other relevant impacts are beyond the scope of this research because they are highly dependent on the location of the WFs. These include visual impact (Ladenburg et al. 2013), noise impact (Kadellis et al. 2012), impact on biodiversity (May et al. 2017), bird mortality (Marques et al. 2014), or electromagnetic interference (Taylor et al. 2015), among others (Klain et al. 2018).

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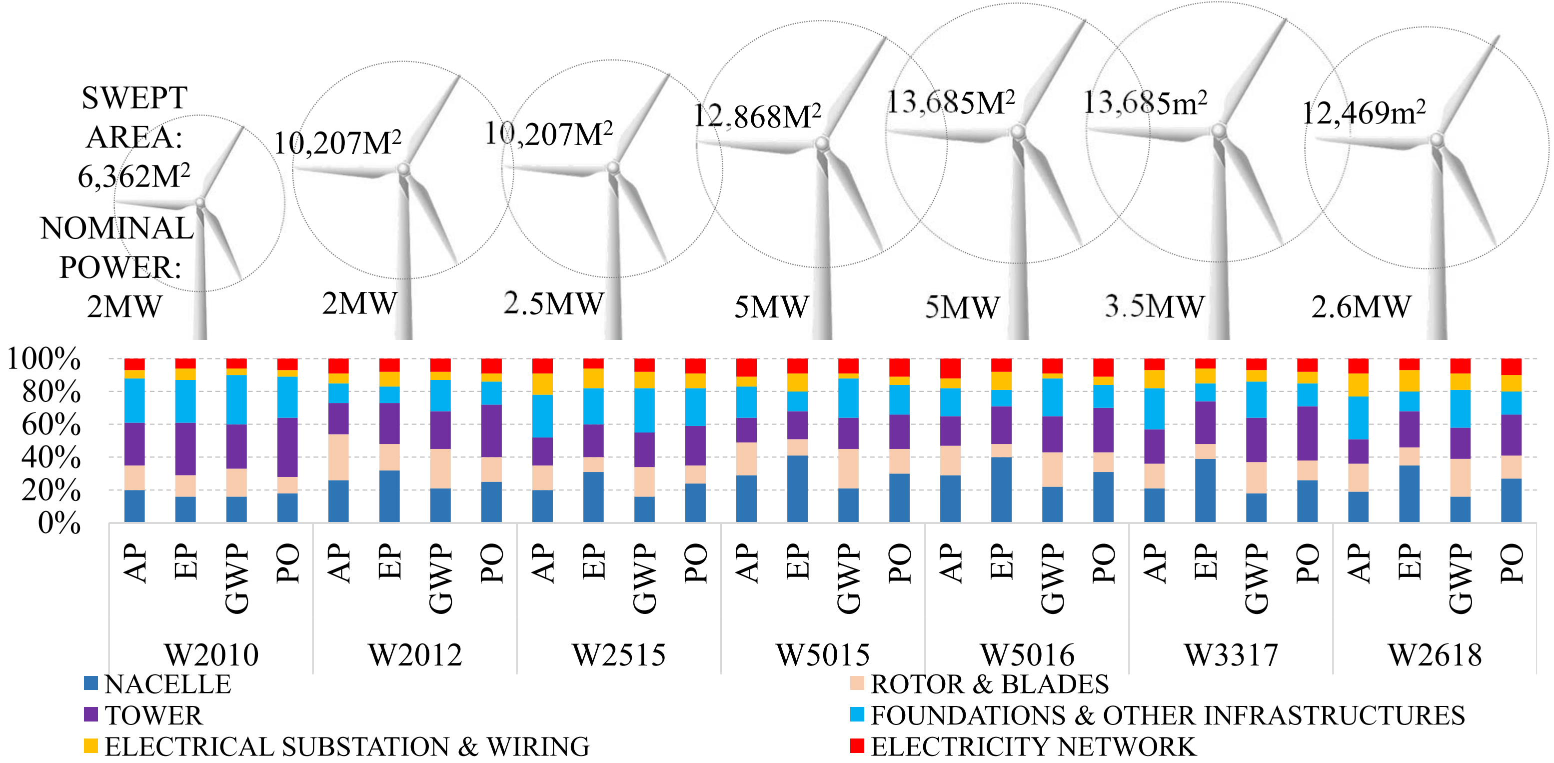
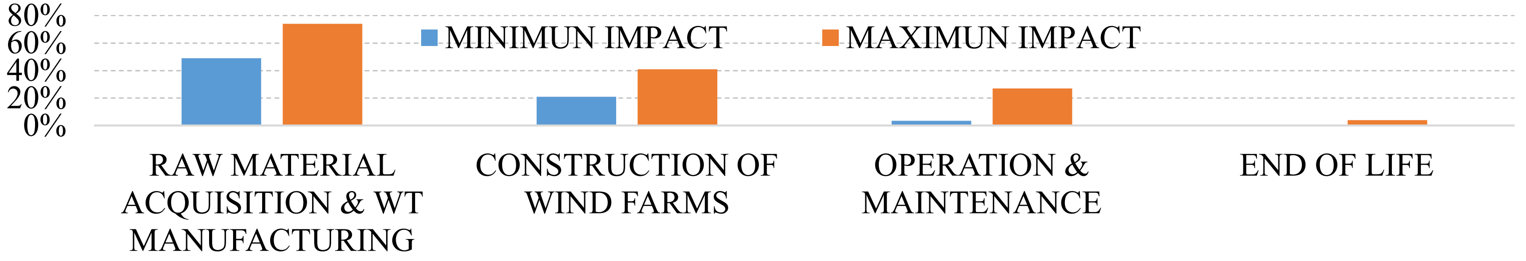
Graphical Abstract

CONTRIBUTION OF EACH SUBSYSTEM TO THE OVERALL ACIDIFICATION POTENTIAL (AP), EUTROPHICATION POTENTIAl (EP), GLOBAL WARMING POTENTIAL (GWP) AND PHOTOCHEMICAL OZONE (PO) IMPACT PER 1 KWH OF ENERGY GENERATED AND DISTRIBUTED



ENVIRONMENTAL IMPACTS BY LIFE CYCLE PHASE



ANNUAL AVERAGE INCREASE IN THE AP, EP, GWP AND PO RELATED TO THE LAUNCH YEAR