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# Environmental Impact of Modern Wind Power under LCA Methodology

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## 1. Introduction

Renewable energy sources constitute an alternative to fossil fuels and their problems, which are, on the one hand, the pollution and CO<sub>2</sub> emissions that they produce and, on the other hand, the diminution of reserves, in addition to other economical and political problems, such as their increasing prices and the economic dependence of non-producers countries on those that produce fossil fuels.

At the present time, renewable energy, and particularly wind power energy, is becoming increasingly relevant in the world's electricity market, based on its advances and on the legislative support of governments in several countries (Río del & Unruh, 2007; Jager-Waldau, 2007; Karki, 2007; Breukers & Wolsink, 2007), for instance with legal frameworks presenting stable and lasting premiums. Figure 1 shows the contribution and the provisions of wind power to the electricity supply network in several countries, both at a European and world level; current forecasts predict that wind power will contribute 12% of the global demand for electricity by 2020 (GWEC, 2005). This huge boom in implementation and forecasts of this power source justify the need to increase its people's understanding (Jungbluth et al., 2005; Gurzenich et al., 1999), based on scientific studies, especially from the point of view of its environmental impact.

Wind power produces electrical energy from the kinetic energy of the wind, without directly producing any pollution or emissions during the conversion process, but this does not mean that it is free of contamination or CO<sub>2</sub> emissions. The question is that it should be considered that there is an environmental impact due to the manufacturing process of the wind turbine and the disposal process at the end of the wind turbine life cycle. And this environmental impact should be quantified in order to compare the effects of the production of energy, and to analyse the possibilities of improvement of the process from that point of view.

Thus, the aim of this chapter is to show a methodology of analysis of the environmental impact of the wind energy technology, considering the whole life cycle of the wind power systems. The application of the ISO 14040 standard (ISO, 1998) allows us to quantify the overall impact of a wind turbine and each of its components from a Life Cycle Assessment (LCA) study. It also allows us to analyse the issues that produce more impact and the aspects that could be improved in order to reduce the effective impact. The LCA model has been developed with the purpose of determining and quantifying the related emissions and

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the impact of wind energy production technology; additionally, the LCA model can be used to define the energy payback time (Martínez et al., 2009; Martínez et al., 2009b; Martínez et al., 2009c).

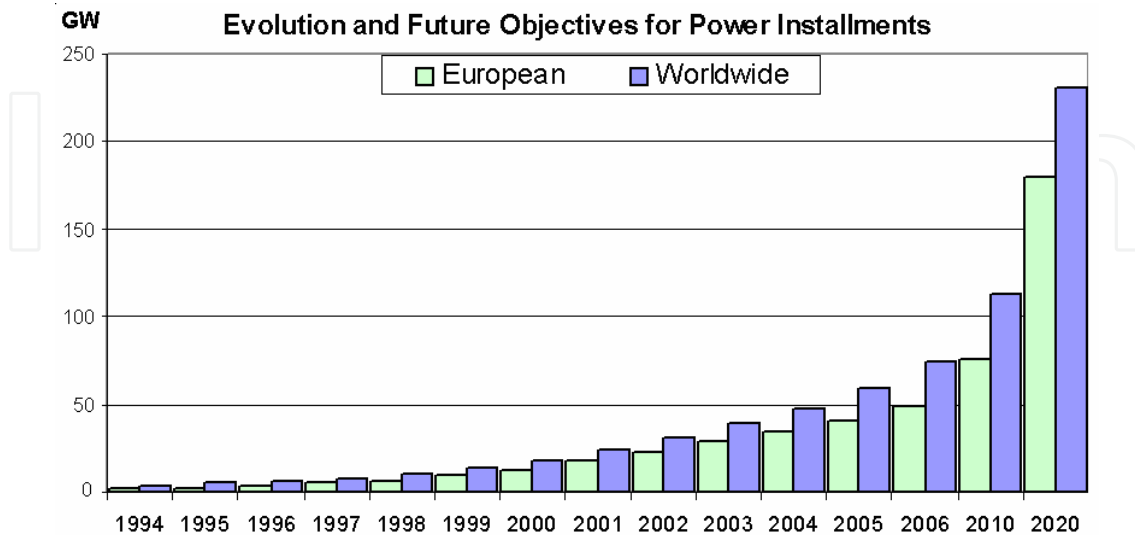


Fig. 1. Evolution and future objectives for wind power instalments

Within the existing LCA studies, there are several ones based on renewable energies in general (Gurzenich et al., 1999; Góralczyk 2003), which do not analyse in detail the LCA of a wind turbine. Reference (Gurzenich et al.,1999), for instance, shows (in its section 2) a comparison of the results of several renewable energy sources, without actually explaining in detail the LCA made in each case, and then focuses on the development of dynamic life cycle assessment as a central part of the study. There are also more specific studies on wind turbines, but they are generally based on older machines and lower rated power, less than 1 MW (Celik et al., 2007; Jungbluth et al., 2005; Ardente et al. 2008), or they refer to hybrid technologies (Khan et al., 2005). In the reference (Celik et al., 2007), micro-turbines and low power urban installation, for example, are studied. The work (Jungbluth et al., 2005) analyses the rapprochement of the database Ecoinvent to wind powers, focusing on studying wind turbines with power ranges from 30 kW to 800 kW. Reference (Ardente et al., 2008) deepens in the LCA of a wind farm with 11 turbines of 660 kW rated power. Reference (Khan et al., 2005) develops an LCA on a hybrid system of wind turbine with fuel cells, with a wind turbine of 500 kW rated power. In addition to these studies about low-power turbines, there are also other analyses focused on multi-megawatt wind turbines, as for instance references (Tryfonidou & Wagner, 2004; Douglas et al., 2008), both of which are focused on offshore wind turbines. On the other hand, there are indeed studies based on multi-megawatt wind turbines, but basically outside the LCA point of view, and focused exclusively on the potential of wind generation of certain areas or regions (Ben Amar et al., 2008; Carolin Mabel & Fernandez, 2008; Wichser & Klink, 2008).

On the other hand, such as it has been previously mentioned, Life Cycle Assessment (LCA) methodology (ISO, 2006) is useful for analysing the environmental impact occasioned by any type of product or process; however, the results obtained with LCA present some uncertainties that have to be considered and assessed in an appropriate way. In general, these LCA uncertainties can be classified into, at least, five types: parameter uncertainty, model uncertainty, spatial variability, temporal variability, and uncertainty due to choices.

For this reason, one of the purposes of this work is to assess the relevance of different choices that have been made during the development of the LCA. Five alternative scenarios have been studied. The first one (AS1) represents an increase in maintenance during the lifetime of this wind turbine. The second alternative scenario (AS2) analyses an increase in the needs of material and energy used. The third scenario (AS3) studies a change in the percentage of recycled materials during the disposal and waste treatment of the wind turbine. The fourth alternative scenario (AS4) analyses a change in the composite waste treatment of the blades at disposal time, from landfill to recycling. Finally, the fifth scenario (AS5) analyses the effect of an increase in the estimated annual production of the wind turbine (Martínez et al., 2009; Martínez et al., 2009b; Martínez et al., 2009c).

These scenarios can facilitate to assess the degree of uncertainty of the developed LCA due to choices made. But this study does not analyse the uncertainty due to imprecise knowledge of the different parameters used in the Life Cycle Inventory (LCI), the spatial and temporal variability in different parameters of the LCI, or the uncertainty due to the inaccuracy and the simplification of the environmental models used.

Finally, another aspect to consider when analysing the environmental impacts by using LCA methodology is the choice of the method used. This chosen method is rarely discussed, and although there exist several works discussing the topic (Schulze et al., 2001; Brent & Hietkamp, 2003; Dreyer et al., 2003; Pant et al., 2004; Bovea & Gallardo, 2006; Renou et al., 2008; Hung & Ma, 2009), usually they focus on specific case studies, and no one is focused on the specific case of renewable energy. Hence it is legitimate to ask whether the LCA results may be influenced by the choice of the LCIA method, between all the scientifically sound methods. This is a key issue, especially if the results of the assessment should be presented to non LCA specialist people. For that reason throughout this chapter an overview of the influence that this choice may have on the final result is provided.

All these analysis, studies and results summarize the work that has been carried by the research group in recent years and have driven to various scientific publications in several important journals related to environment and renewable energy (Martínez et al., 2009; Martínez et al., 2009b; Martínez et al., 2009c). This chapter explain these works, in a summarised and qualitative way, but all the quantitative information should be obtained from the mentioned published works of the group.

## 2. LCA methodology

### 2.1 Method and scope

For presenting the main points of the environmental impact study of the wind turbine, the method CML Leiden 2000 has been selected in order to avoid subjectivity (Guinée et al., 2001). The midpoint impact categories considered have been:

- Abiotic depletion (AD): This impact category is concerned with protection of human welfare, human health and ecosystem health, and is related to extraction of minerals and fossil fuels. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration of reserves (Goedkoop et al., 2004).
- Climate change (GW): Climate change can result in adverse affects upon ecosystem and human health and is related to emissions of greenhouse gases to air. GW change factor is expressed as global warming potential for 100 years time horizon, in kg carbon dioxide/kg emission (Goedkoop et al., 2004).

- Stratospheric ozone depletion (OLD): This category is related to the fraction of UV-B radiation reaching the earth surface. The characterisation model defines the ozone depletion potential of different gasses (kg CFC-11 equivalent/kg emission) (Goedkoop et al., 2004).
- Human toxicity (HT): This impact category is related to exposure and effects of toxic substances for an infinite time horizon. For each toxic substance, human toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al., 2004).
- Fresh-water aquatic eco-toxicity (FWAE): It is related to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water, and soil, for an infinite time horizon. For each toxic substance, eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al., 2004).
- Marine eco-toxicity (MAE): This impact category is related to the impact on marine ecosystems. As in the human toxicity category, the eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al., 2004).
- Terrestrial eco-toxicity (TE): This impact category is related to the impact on terrestrial ecosystems. As in the human toxicity category, the eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al., 2004).
- Photochemical oxidation (PO): This category is related to the formation of reactive substances (mainly ozone) that are injurious to human health and ecosystems and which may also damage crops. The impact potentials are expressed as an equivalent emission of the reference substance ethylene, C<sub>2</sub>H<sub>4</sub> (Hauschild & Wenzel, 1998).
- Acidification (AC): This category is related to the acidifying substances that cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, and materials. The major acidifying substances are SO<sub>2</sub>, NO<sub>x</sub>, HCl and NH<sub>3</sub>. For emissions to air, the acidification potential is defined as the number of H<sup>+</sup> ions produced per kg substance relative to SO<sub>2</sub> (Bauman & Tillman, 2004).
- Eutrophication (EU): This category is related to all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water, and soil. Nitrogen (N) and phosphorus (P) are the two nutrients most implicated in eutrophication (Bauman & Tillman, 2004).

In addition, an energy input assessment was carried out, using cumulative energy demand to calculate the total direct and indirect amount of energy consumed throughout the life cycle (Boustead & Hancock, 2003; Pimentel, 2003). The software used in the environmental analysis was SimaPro 7.0 by Pré Consultants (SimaPro, 2006).

A LCA model of a wind turbine with Double Feed Inductor Generator (DFIG) has been developed with the object of identifying the main types of environmental impact throughout the life cycle, in order to define possible ways of achieving environmental improvements for the particular type of wind turbine analysed, or for similar ones. The wind turbine is a Gamesa onshore wind turbine, G8X model, with 2 MW rated power, and general dimensions: 80m rotor blade, 5,027m<sup>2</sup> sweep area, and 70m height.

The wind turbine is installed in the Munilla wind farm, in northern Spain, where it has been analysed during the different stages of its life cycle, from cradle to grave, taking into consideration the production of each of its component parts, the transport to the wind farm, the installation, the start-up, the maintenance and final decommissioning, with its subsequent disposal of waste residues. An LCA model of a wind turbine can be appreciated in (Martínez et al., 2009).

## 2.2 System boundary

Within the limits of the system studied fall the construction of the main components of the turbine, the transportation of the turbine to the wind farm, the assembly, the installation, and the start-up, as well as the process of dismantling the wind turbine and the subsequent treatment of generated waste. A graphical representation of the limits of the system can be seen in (Martínez et al. 2009c).

Outside the limits of the system under study fall the system of distribution of the electricity generated by the wind turbine; that is, the medium-voltage wiring, the transformer substation, and the national electrical power network.

## 2.3 Functional unit

The aim of the work is to know the environmental impact of wind power, and to quantify it, but it is necessary to relate this impact to the electricity generated, in order to be able to make a posterior comparative study with regard to other types of energy producing technology. Thus, the functional unit has been defined as the production of 1 kWh of electricity.

## 2.4 Data collection

A wind turbine consists of many components, which also comprise many sub-components, of different nature and eventually with mechanical, electrical, and electronic parts; so, it is difficult to gather from suppliers the information on all the parts that compose the turbine. We have focused on compiling the life cycle inventory (LCI) data on the most important components, specifically the foundation, the tower, the nacelle, and the rotor. In the few cases in which the data found have not been sufficiently reliable and proven, quasi-process information from commercial Ecoinvent database of SimaPro software has been used.

For instance, the materials and energy used in the diverse components have been incorporated into the model using data provided by Gamesa. The distances of transport have been calculated from specific maps as far as the real emplacement of the Munilla wind farm. The main materials that constitute the most important components of the turbine, as well as the selected reference database Ecoinvent, can be seen in (Martínez et al. 2009), specifically the Inventory per component and the Ecoinvent process selected per material.

The owner company of the wind farm performs the maintenance operations, and the information about them is recorded in its environmental management system according to the ISO 14001 standard (ISO, 2004). Based on this important information, all the maintenance operations have been taken into account during the operational phase, such as quantities of oil and grease used or replacement of filters, and transport, among others. Transport processes include the impact of emissions caused by the extraction and production of fuel and the generation of energy from that fuel during transport (Spielmann & Scholz, 2005).

## 2.5 Key assumptions

As previously mentioned, the LCA model developed includes both the turbine and the foundations that support it, but not the system for connection to the grid (medium voltage lines and transformer substation).

A series of cut-off criteria have been established in order to develop the study, by defining the maximum level of detail in the gathering of data for the different components of the

wind turbine. The main cut-off criterion chosen is the weight of each element in relation to the total weight. This limitation in data collection does not mean a significant weakening of the final results obtained, but allows us to streamline, facilitate, and adjust the LCA study to make it more flexible.

The characterisation of each component has been obtained from the most important basic data of the manufacture, which are: the raw material required, the direct consumption of energy involved in the manufacturing processes, and the information of transport used. The information published by Riso National Laboratory has been used when it has not been possible to obtain the energy cost of the manufacturing process directly. This information for specific substances includes the primary energy consumption use related to the production, transportation, and manufacture of 1 kg of material (Etxeberria et al., 2007).

Thus, this LCA has been performed under the following conditions, due to limitations of time and cost:

- The cut-off criterion used has been the weight of the components. The elements that have been taken into account, altogether, make up 95% of the foundations, 95% of the tower, and 85% of the nacelle and rotors.
- All data on electricity has been obtained from the SimaPro database (Frischknecht & Rebitzer, 2005; Frischknecht et al., 2005).
- The wind turbine lifetime is 20 years.
- The assumed current recycling rate of waste wind turbine has been estimated based on the wind farm decommissioning projects prepared by the company (GER, 2004). (Martínez et al., 2009) presents a table with the type of dismantling of the different materials.
- The production is 4 GWh per wind turbine and year.
- One replacement generator has been estimated during the complete lifetime of the wind turbine.

According to the requirements of the standard ISO14044 (ISO, 2006), allocation has been avoided, since in this study only the production of electrical power is considered as the function of the system and, therefore, allocation has not been considered in any component or process.

## 2.6 Analysed scenarios

The LCA above mentioned contains several uncertain parameters, and therefore, a variability analysis has been developed in order to find the impact of variations in the most significant of these parameters. A series of variables on which to focus the research have been selected, in order to develop the variability analysis of the results of the LCA. These selected variables are presented in the following scenarios, explained in detail in (Martínez et al., 2009c):

- AS1: It is focused on increasing corrective maintenance throughout the life of the turbine. This aspect of the increased requirements for maintenance is of vital importance in the world of wind power, and it is the reason why predictive maintenance systems reducing these major corrective to the minimum are being investigated nowadays. With the aim of considering the various possible alternatives, three alternative scenarios have been considered.
- AS2: It has been established, considering an increase in energy and in materials, in order to compensate for the effect of possible elements that have not been included in

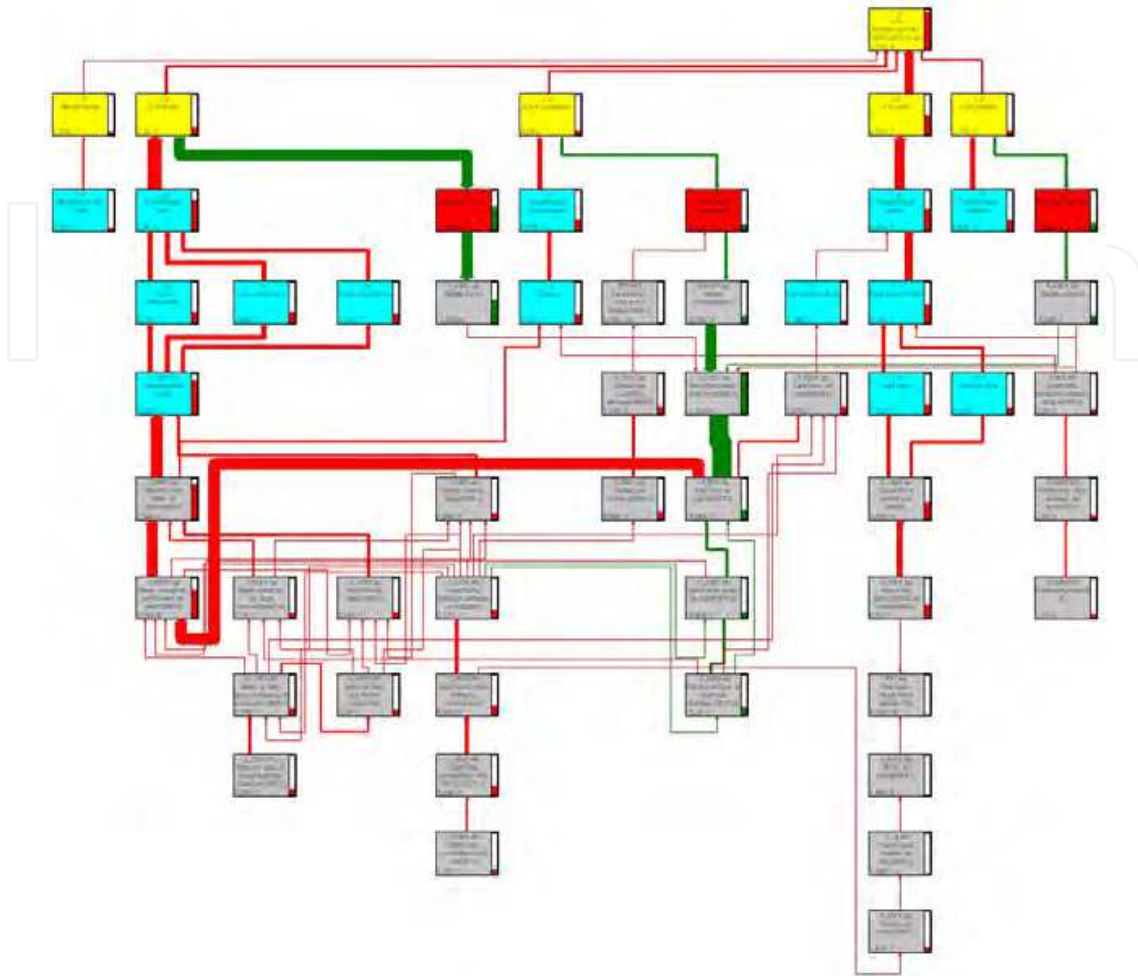


Fig. 1. ACV structure of the basic scenario

the LCA because of the use of the cut-off criteria. Moreover, each increase has been analysed separately in order to better assess the impact of each deviation relative to the basic scenario, according to the following scenarios:

- AS21: In this scenario only the increases corresponding to the energy and transportation required in the LCA are applied.
- AS22: In this scenario an increase in the consumption of different materials used throughout the lifetime of the wind turbine is contemplated.
- AS3: It has been established in order to assess the impact of reducing the criteria when the recycling process of dismantling and disposal is carried out in practice.
- AS4: A recycling of part of the composite material of the blades has been considered in this alternative scenario. This tries to assess the trend and the future changes of composite materials recycling, since the current industrial regulations begins to consider unfavourably sending composites to landfill.

Figures 1 to 7 represent the ACV of the seven previous scenarios.

The Disposal considerations of the basic scenario are published in a table in (Martínez et al. 2009c); in that work another Scenario is also analysed, AS5, associated to 3000 equivalent hours, i.e. 6 GWh annual production.



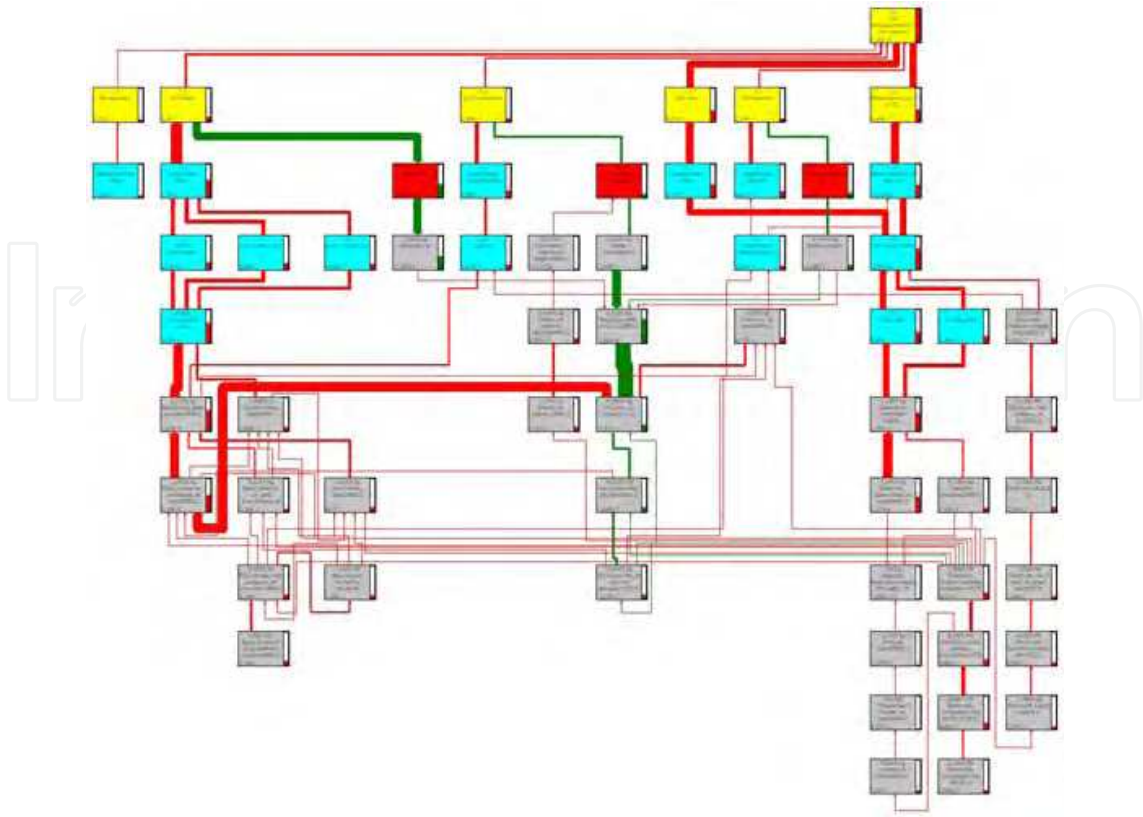


Fig. 2. ACV structure of the alternative scenario AS11

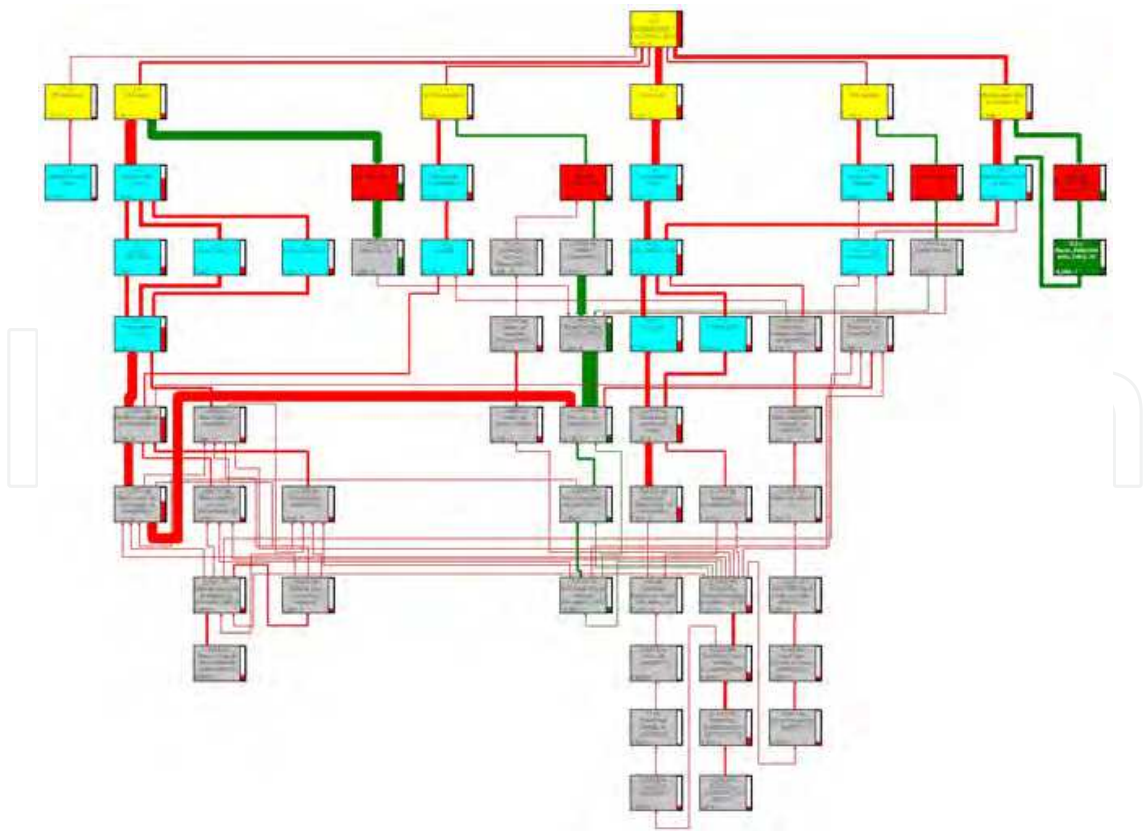


Fig. 3. ACV structure of the alternative scenario AS12

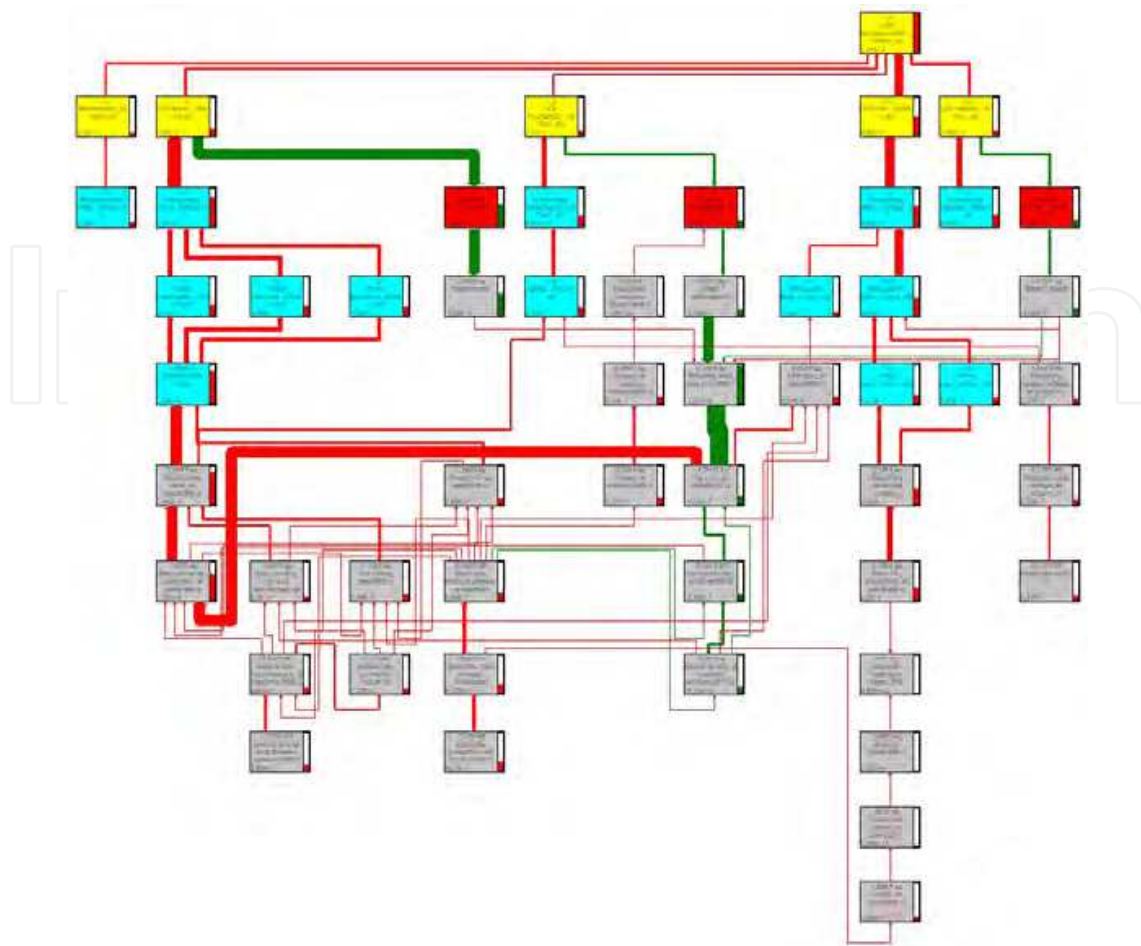


Fig. 4. ACV structure of the alternative scenario AS21

## 2.7 Comparative of LCIA methods

Seven methods have been selected in order to develop the life cycle impact assessment for the comparative analysis.

- CML 2 baseline 2000 V2.03 / World, 1990
- Eco-indicator 99 (E) V2.03 / Europe EI 99 E/E
- Ecopoints 97 (CH) V2.03 / Ecopoints
- EDIP/UMIP 97 V2.03 / EDIP World/Dk
- EPS 2000 V2.02 / EPS
- IMPACT 2002+ V2.02 / IMPACT 2002+
- TRACI V2.00

In the comparative results obtained with each method, the references have been, on the one hand the impact categories related to energy, and, secondly, those related to toxicity. The first ones are summarized in acidification, nutrient enrichment (eutrophication), global warming (climate change), abiotic depletion and ozone layer depletion. And those relative to toxicity are concentrated in ecotoxicity and human toxicity. As expected not all impact methods present these categories or other directly comparable. In these cases the most suitable approximation has been searched, within the different impact categories available in each method, or when it has not been possible to find one or more categories of comparable impact, they have been eliminated from the comparative LCIA

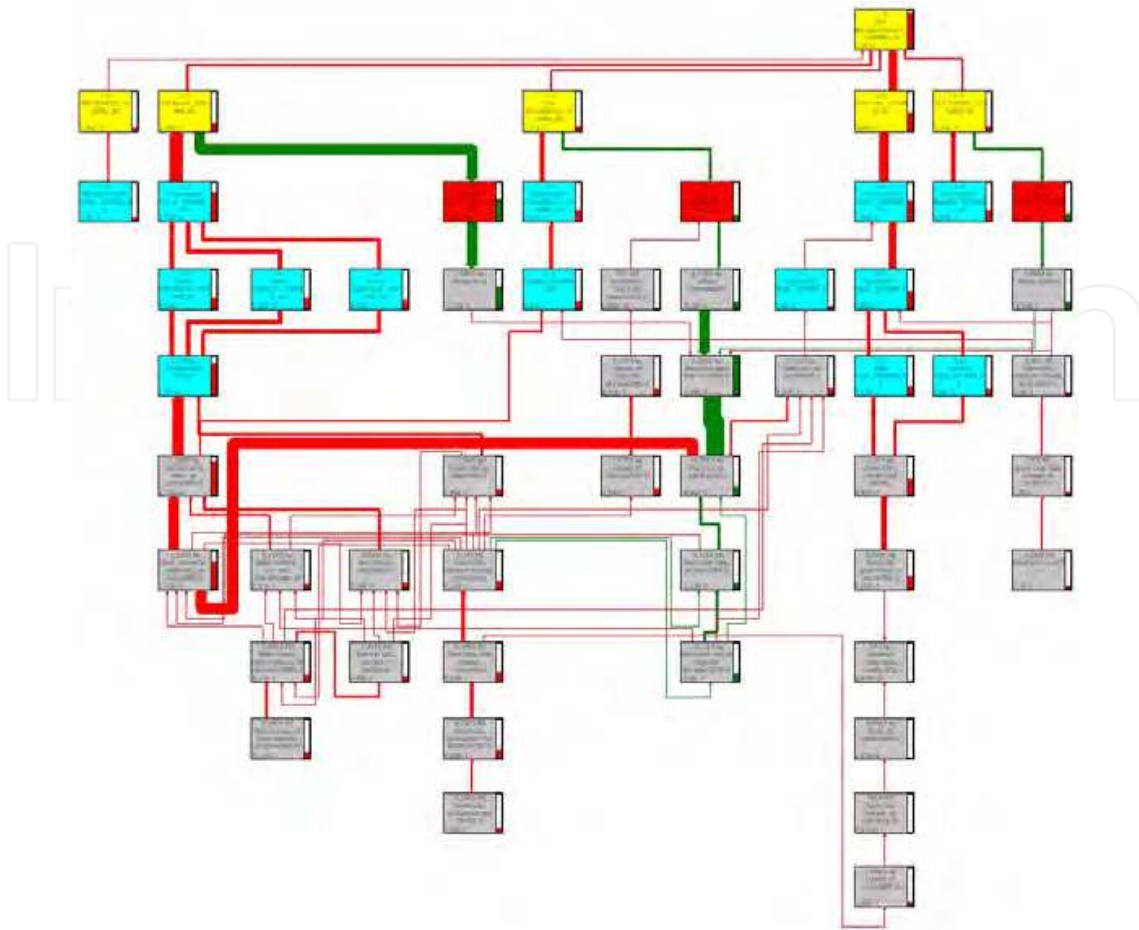


Fig. 5. ACV structure of the alternative scenario AS22

### 3. Results

#### 3.1 Environmental impact

The results obtained per impact category are shown in (Martínez et al. 2009), especially in the tables Characterization results, Percentage reduction of environmental impacts of wind turbine versus the electricity mix of Spain, and Environmental impact prevented by recycling, as well as in their following analysis of results of that reference (Martínez et al. 2009).

#### 3.2 Cumulative Energy Demand

The Cumulative Energy Demand (CED) is calculated for five classes of primary energy carriers: fossil, nuclear, hydro, biomass and others (wind, solar, geothermal). Differences for different types of cumulative energy demands are mainly due to the consideration of location-specific electricity mixes. The preponderance of non-renewable energies in Spain, especially energy from fossil fuels, is clearly demonstrated (see Table of Cumulative Energy Demand results, in Martínez et al. 2009).

##### 3.2.1 Energy payback time

Another important aspect is to evaluate the Energy Payback and Energy Yield Ratio. The definition of both terms is as follows:

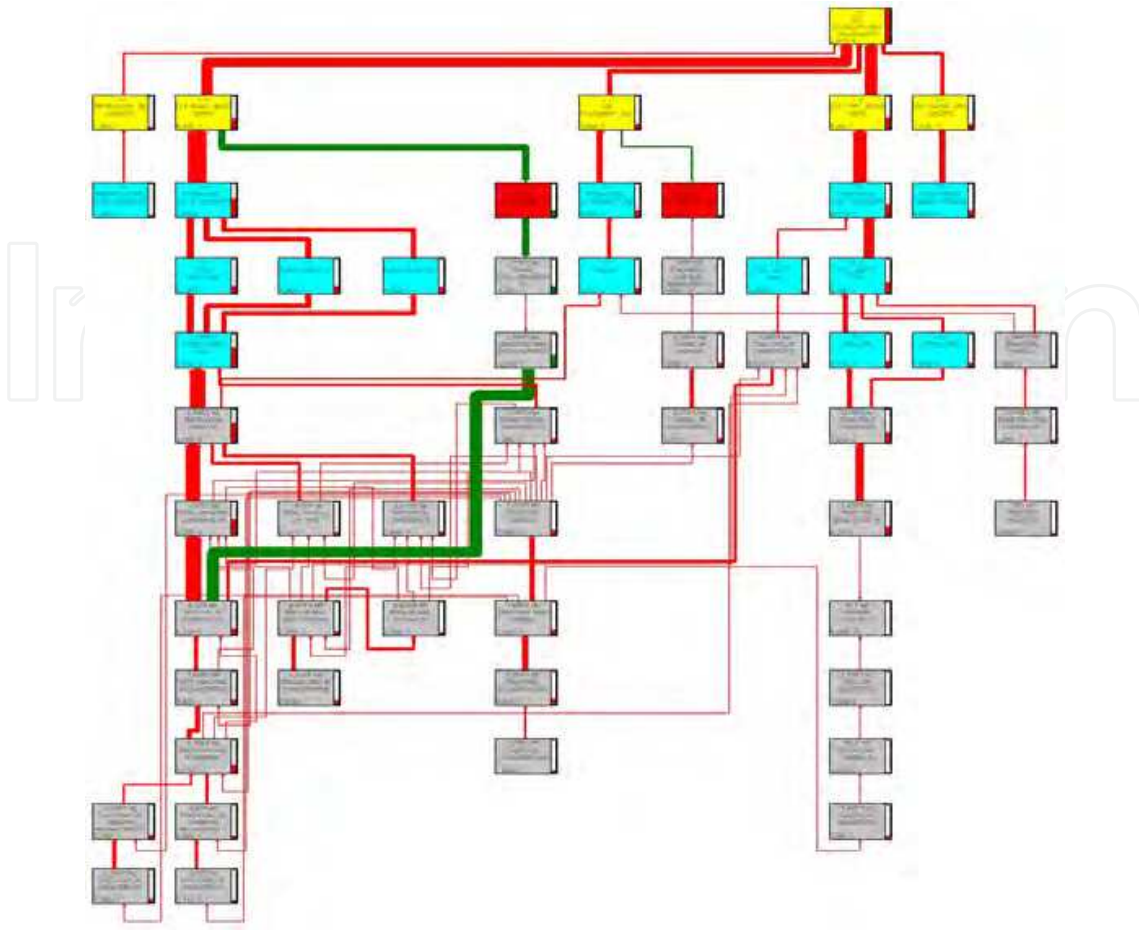


Fig. 6. ACV structure of the alternative scenario AS3

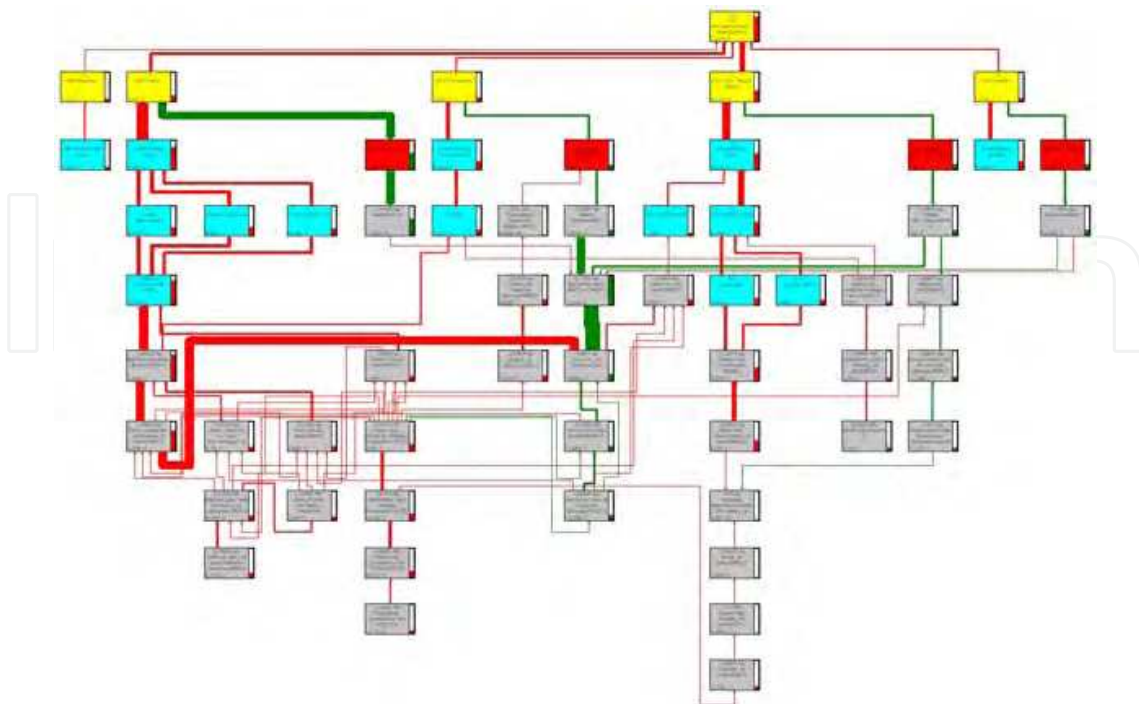


Fig. 7. ACV structure of the alternative scenario AS4

- Energy payback time: this term indicates the years that the system under study must be operating to return the amount of energy that has been needed for their manufacture, start-up, and operation throughout its lifespan.
- Energy yield ratio: This term represents the relationship between the energy generated by the system throughout its lifetime and the energy consumed by the system (CED).

(Martínez et al. 2009) presents a table with the CED value of the wind turbine. From this basis and with the average annual production of wind turbine (Troen & Petersem, 1991), the energy payback time and the energy yield ratio are obtained (Martínez et al. 2009). In addition, the time needed to compensate for the environmental impact generated by manufacturing, launching and operating of wind turbines, by the reduction of requirements for conventional electric energy generation has been calculated (Martínez et al. 2009). This study has considered again the electricity mix in Spain from the database Ecoinvent.

### 3.3 Results of the variability analysis

The results of the variability analysis are described, depending on the different scenarios and their characteristics (Additional maintenance, Additional inputs of materials and energy, Reduction by half of the recycling, Inclusion of blade recycling, and Increased power generation), in (Martínez et al., 2009c), where some interesting tables present the results, which are then analysed and explained. The most interesting tables are: LCA results of the alternative scenarios AS11, AS12 and AS13 and the basic scenario, Percentage of variation of the alternative scenarios AS11, AS12 and AS13 relative to the basic scenario, Percentage of variation of the alternative scenarios AS21 and AS22 relative to the basic scenario, Percentage of variation of the alternative scenario AS3 relative to the basic scenario, LCA results of the alternative scenario AS4 and percentage of variation relative to the basic scenario.

### 3.4 Results of the methods comparative

#### 3.4.1 Environmental impact

Of the different impact categories studied, we can highlight the results, among others, of the impact categories of acidification and Human Toxicity. The results obtained after comparing the level of acidification in different LCIA under study are presented in (Martínez et al., 2009c). The results are very similar although a small difference can be appreciated between two groups, with results very closed between the methods of every group, the first one made up of CML 2000, EDIP 96, EPS, TRACI and Ecopoints methods, and the second one which comprises Eco Indicator 99 and Impact2002 methods. This can be explained by several reasons:

- Eco Indicator 99 combines in one single LCIA impact, acidification and eutrophication.
- In the case of Impact2002 the characterization factors for the category TAN are taken directly from Eco Indicator 99 (Goedkoop & Spriensma, 2000).
- Eco Indicator 99 and Impact2002 seems to give a higher importance to nitrogen oxides in acidification phenomena compared with the rest of the methods analysed in the work.

#### 3.4.2 Recycling

Following, the effect of using different LCIA in the results of the positive effect of recycling in the performed LCA is examined. As expected the same relationships found in the specific analysis of each category are held when analysing only recycling, although it could be noted, for example, the results obtained in the case of some impact category, with almost complete unanimity on the importance of recycling of the metallic material of the turbine tower.

### 3.4.3 Sensitivity analysis

Likewise, when studying the results for each of these alternative scenarios in the sensitivity analysis performed, it can be observed that the choice of the LCIA method leads to emphasize, to a certain or lesser extent, various alternative scenarios. Generally, it can be deduced that in all impact categories studied, there are one or more LCIA's alternative scenarios that provide major increase in that category for the base case.

## 4. Conclusions

Throughout this chapter, a methodology of analysis of the environmental impact generated by a wind turbine has been presented, based on previous works of the research group composed of the authors. From the results obtained, an important conclusion is the significant impact generated by the turbine blades and, especially, their non-recycling status. Here is found a need for further research into recycling processes of this type of material (Pickering, 2006; Cunliffe et al., 2003; Marco de et al., 1997; Torres et al., 2000; Williams et al., 2005; Vallee et al., 2004; Perrin et al., 2006), as well as for their practical application in the final dismantling and waste treatment phases of wind turbines. Another material that presents a significant impact within the study is the copper (Lunt et al., 2002; Norgate & Rankin, 2000) present in the nacelle of the turbine, but in this case with the advantage of being a recyclable material (Norgate et al., 2007).

In any case, although there are components with a significant environmental impact within the turbine, it has also been verified that these impacts are much smaller than those generated by conventional power plants in operation, with reductions in the impact about 95%, depending on the category. In addition, the energy payback time (time regarding the energy required to produce and implement a turbine) is less than one year, much smaller than the useful lifetime of the system, which is at least 20 years.

Moreover, the different uncertainties arising from the options given during the development of the LCA of a wind turbine have been analysed throughout this work. Five different scenarios within the LCA of a multimegawatt wind turbine have been analysed. In addition, the impact that these scenarios may present on the final LCA has also been assessed. From the results can be clearly emphasized the specific case of large corrections in the maintenance phase. Undoubtedly, the choices made at the turbine maintenance stage have an important effect on the results of the LCA. Therefore it is necessary to analyse and define more precisely the average of major corrections that may experience a model of wind turbine along its 20 years of life. Another issue that significantly influences the final results of the LCA study of the multi-megawatt wind generator in question is the considerations made about recycling and reuse of components and materials. A clear example is the impact of materials such as the fibreglass of the blades of the wind turbine when they are not recycled but sent directly to landfill.

Finally, seven LCIA methods have also been compared in relation to different impact categories, and significant discrepancies have been found in the results. Furthermore, some of these methods may not consider impact categories that are currently debated, which may be relevant to the LCA study being conducted.

On many occasions, a LCA practitioner may simply select a LCIA methodology provided as part of a LCA software tool. In these cases, the impact category, indicator and model selection, and classification have been preselected for the user. This is appealing from the practitioner's point of view since it is faster and less costly. However, it must be noted and

cautioned that depending on the methodology chosen and the impact categories of interest, the user may obtain qualitatively different results.

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This book is the result of inspirations and contributions from many researchers of different fields. A wide variety of research results are merged together to make this book useful for students and researchers who will take contribution for further development of the existing technology. I hope you will enjoy the book, so that my effort to bringing it together for you will be successful. In my capacity, as the Editor of this book, I would like to thank and appreciate the chapter authors, who ensured the quality of the material as well as submitting their best works. Most of the results presented in the book have already been published on international journals and appreciated in many international conferences.

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