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Life cycle assessment of a multi-megawatt wind turbine

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ABSTRACT

At the present moment in time, renewable energy sources have achieved great significance for modern day society. The main reason for this boom is the need to use alternative sources of energy to fossil fuels which are free of CO_2 emissions and contamination. Among the current renewable energy sources, the growth of wind farms has been spectacular. Wind power uses the kinetic energy of the wind to produce a clean form of energy without producing contamination or emissions. The problem it raises is that of quantifying to what extent it is a totally clean form of energy. In this sense we have to consider not only the emissions produced while they are in operation, but also the contamination and environmental impact resulting from their manufacture and the future dismantling of the turbines when they come to the end of their working life. The aim of this study is to analyse the real impact that this technology has if we consider the whole life cycle. The application of the ISO 14040 standard [ISO. ISO 14040. Environmental management – life cycle assessment – principles and framework. Geneva, Switzerland: International Standard Organization; 1998.] allows us to make an LCA study quantifying the overall impact of a wind turbine and each of its components.

Applying this methodology, the wind turbine is analysed during all the phases of its life cycle, from cradle to grave, with regard to the manufacture of its key components (through the incorporation of cut-off criteria), transport to the wind farm, subsequent installation, start-up, maintenance and final dismantling and stripping down into waste materials and their treatment.

1. Introduction

At the present time, renewable energy, and particularly wind power energy, is becoming increasingly relevant in the world's electricity market. Over the last few years renewable sources of energy have won the legislative support of governments in several countries [2–6]. This support has taken the form of various legal frameworks with stable and lasting premiums. If we look at the current scene in the implementation of renewable energy, we can see the rapid advance made by wind power and its significant contribution to the electricity supply network in several countries, both at European and world level (see Fig. 1). Wind power supplies less than 1% of electricity now [7]. In the EU, 4% of the power installed originates from wind power and in Spain the figure is 9% [8]. Current forecasts predict that wind power will contribute 12% of the global demand for electricity by 2020 [9]. This huge boom in implementation and forecasts for wind power installation makes clear the need to increase people's understanding of this power source [10,11]. Although there are several analyses about environmental impact of renewable energies [12–15], not many life cycle assessment studies exist for current wind turbines with high rated power [16–18]. So an LCA model has been developed with the purpose of being able to assess the wind energy and the related emissions to produce current wind energy production technology. Furthermore, the LCA model can be used to define the energy payback time.

2. Life cycle assessment of a wind turbine

2.1. Goal, scope and background

The LCA model which has been developed seeks to identify the main types of impact on the environment throughout the life cycle of a wind turbine with doubly fed inductor generator (DFIG). The study has specifically focussed on the Gamesa onshore wind turbine model G8X with 2 MW rated power installed in the Munilla wind farm. This wind farm is located in the autonomous community of La Rioja, in northern Spain. This is a complex terrain located at 1200 m altitude. The general dimensions of this wind turbine are 80 m rotor blade, 5027 m^2 sweep area and a height of 70 m. This project is the first phase of a more wide-reaching one which seeks

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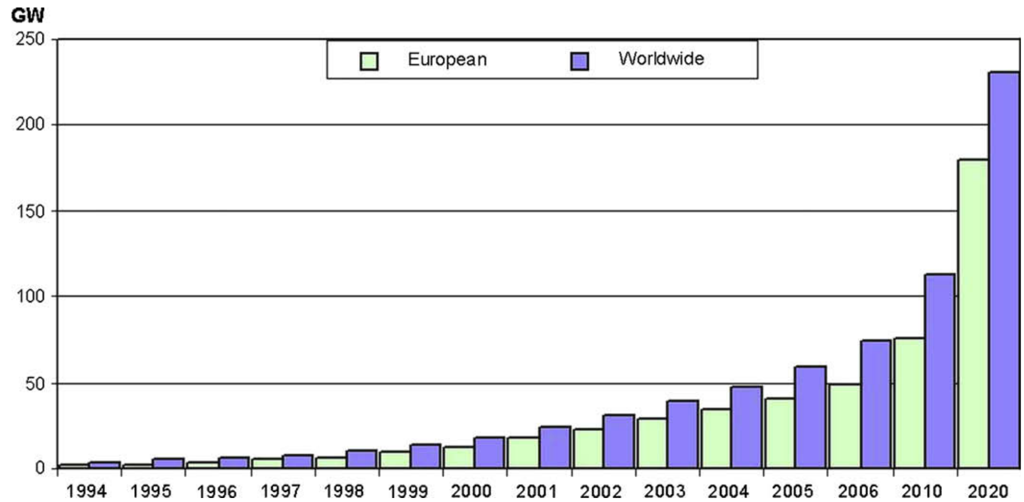

Fig. 1. Evolution and future objectives for wind power installments.

to define possible ways of achieving environmental improvements for this particular type of wind turbine. To achieve this goal we have started by analysing the wind turbine during the various stages of its life cycle, from cradle to grave, taking into consideration the following: the manufacture of each of its component parts, transport to the wind farm, installation, start-up, maintenance and final decommissioning with its subsequent disposal of waste residues.

2.2. Functional unit

As the functional unit for the system, we have selected the kWh produced by the wind turbine in such a way that it has been possible to obtain a relationship between the environmental impact of the turbine and the electricity generated. In this way it is possible to make a posterior comparative study with regard to other kinds of energy producing technology.

2.3. Life cycle inventory

Fig. 2 shows an outline of the model used for assessing the environmental impact of a wind turbine during its whole life cycle.

A wind turbine consists of many electrical, electronic and mechanical parts and components. The components of a wind turbine, such as the nacelle, also comprise many sub-components and/or electrical parts. It is difficult to gather all the information on all the parts and components from suppliers. We focused on compiling the LCI data on important components such as the base, the tower, the nacelle and the rotor. However, in the few cases in which the data found were not sufficiently reliable and proven, we used quasi-process information from commercial SimaPro software. The materials and energy used in the various components were incorporated into the model using data provided by Gamesa and the commercial databases of SimaPro.

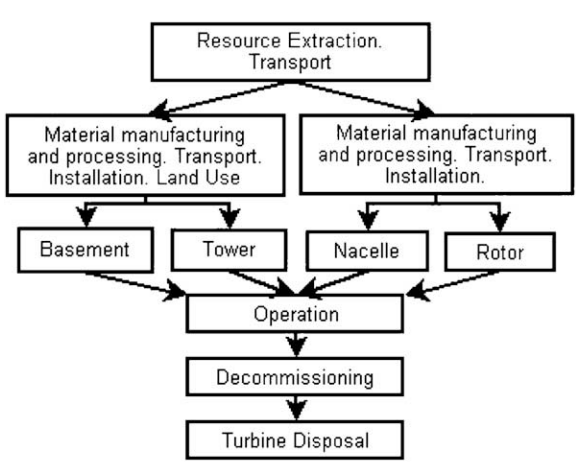

Fig. 2. LCA model of the wind turbine.

When considering transport, distances have been calculated from specific maps as far as the real emplacement of the Munilla-Lasanta wind farm. During the operational phase, all the maintenance operations have been taken into account. These maintenance operations are performed by the owner company of the wind farm and recorded in its environmental management system according to the ISO 14001 standard. Among the maintenance tasks programmed we can check quantities of oil and grease used, replacement of filters and transport, among others.

Below we briefly describe each of the components analysed.

2.3.1. Foundations

The base has a volume of 270 m^3 of concrete and a total weight of 700 t and uses 25 t of iron for the reinforcing bars (see Table 1). The steel ferrule used to connect and support the turbine tower weighs 15 t (see Table 1). During the lifespan of the wind turbine the possible emissions from the foundation into the environment have not been considered. In the decommissioning process it has been assumed that the foundations will be left in place and covered with a layer of 20–30 cm of organic soil [19].

2.3.2. Tower

In the study conducted only the processes of shaping and welding steel have been considered. The surface treatment was considered as irrelevant with regard to the final result of the analysis. Once the whole tower is erected it measures 67 m and weighs 143 t (see Table 1). During the operation of the wind turbine no maintenance work on the tower is provided for. In the decommissioning process of the tower, the material undergoes a recycling process in which losses of material are estimated at 10% [20]. An average material loss rate of 10% has been assumed for recycling process.

2.3.3. Nacelle

The structure of nacelle consists of a bed frame and a nacelle cover made of composite material (prepreg). Inside nacelle are the

Table 1
Key parameters of the life cycle inventory for wind power production

Component	Sub-component	Weight	Materials	Energy
Rotor	Three blades	19.5 t	11.7 t resin 7.8 t fibre glass	20, 15 MWh
	Blade hub	14 t	14 t cast iron	12 MWh
	Nose-cone	310 kg	0.124 t fibre glass 0.186 t resin	0.95 MWh
Foundation	Footing	725 t	700 t concrete 25 t iron	0.4 MWh
	Ferrule	15 t	15 t steel	17,000 MJ
Tower	Three sections	143 t	143 t steel	170,000 MJ
Nacelle	Bed frame	10.5 t	10.5 t iron	9 MWh
	Main shaft	6.1 t	6.1 t steel	5.3 MWh
	Transformer	5 t	0.149 t silica 1.5 t copper 3.3 t steel	200,000 MJ
	Generator	6.5 t	0.195 t silica 2 t copper 4.29 t steel	265,000 MJ
	Gearbox	16 t	8 t iron 8 t steel	495,000 MJ
	Nacelle cover	2 t	0.8 t fibre glass 1.2 t resin	6.2 MWh

main components of the turbine responsible for converting the mechanical rotational energy of the rotor into electrical power. The main components are the main shaft, the gearbox, the generator and the transformer. Taken together, the total weight of these components is around 50 t. During its use and maintenance phase, we have allowed for a complete oil change on the gearbox and the cooling system. Regular lubrication of the gears and other mechanical parts of the system is also provided for. In the decommissioning phase, it is considered that no component is to be reused and that they undergo a recycling process, with a 10% loss of material.

2.3.4. Rotor

The whole unit weighs approximately 35 t (see Table 1). Each blade is 39 m long, weighs 6.5 t (see Table 1) and is made of prepreg material. The nose-cone weighs 310 kg (see Table 1) and is also made of prepreg. The blade hub is made of cast iron and weighs around 14 t (see Table 1). In the decommissioning process at the end of the lifespan, the recycling of the blade hub has been allowed for while all the prepreg from the nose-cone and rotor blades will be sent to the dump.

2.4. Assumptions and limitations

The LCA model developed includes both the turbine and the foundations which support it, leaving aside the system for connection to the grid (medium voltage lines and transformer substation). As is logical, to achieve the global aims set, it is necessary to establish a series of cut-off criteria. In this way, the maximum level of detail in the gathering of data for the various components of the wind turbine is defined. 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 main cut-off criterion chosen is the weight of each element in relation to the total weight. The most important basic data obtained to characterise the manufacture of each component have been the raw material required, direct energy consumption involved in the manufacturing processes, and the type of transport used. In those cases where it has not been possible to obtain the energy cost of the manufacturing process directly, we have turned to the data published by Riso National Laboratory. These data indicate the primary energy consumption use related to the production, transportation and manufacture of 1 kg of material for specific substances [21].

Due to limitations of time and cost, this LCA was performed under the following conditions:

- When site-specific data of sub-components or parts were not available, we adopted other similar databases from SimaPro7.0 [22].
- All data on electricity were obtained from the SimaPro database [23,24].
- As cut-off criteria we have used the weight of the components. We have taken into account those elements which taken together make up 95% of the foundations, 95% of the tower and 85% of the nacelle and rotors taken together.
- The assumed current recycling rate of waste wind turbine was estimated based on the wind farm decommissioning projects prepared by the company (see Table 2).
- A wind turbine lifetime of 20 years.
- A production of 4 GWh/wind turbine per year.
- One replacement generator has been provided for during the complete lifetime of the wind turbine.

2.5. Allocation and impact categories

Allocation may be necessary when a process yields more than one product, i.e. a multifunctional process. Allocation should reflect the physical relationship between the environmental burdens imposed, and the functions delivered, by the system [25]. This study didn't consider allocation in any component or process, since only the production of electrical power is considered as a function of the system.

The ecological effects of carcinogens (C), organic respiration (OR), inorganic respiration (IR), global warming (GWP), radiation (R), depletion of the stratospheric zone (ODP), ecotoxicity (ET), acidification and eutrophication (Acid./Eut.), land use (LU), minerals (M) and fossil fuels (Fuels) are adopted as the impact categories. We followed the Eco-Indicators guideline [26], when we selected the list of impact categories and assessment methods.

2.6. Data quality

Gamesa A/S has collected a valuable quantity of data through their environmental management system. These data are used in the production of the tower, nacelle and blades. Data for the materials have been collected from suppliers.

Data on manufacture of the foundation are based on the knowledge and experience that the firm GER (Grupo Eólicas Riojanas) has acquired over the years in the promotion of wind farms. Information about transport, assembly, erection, installation, maintenance and decommissioning of the wind turbine has been obtained from the GER company, various subcontractors and the different departments of Gamesa A/S.

Table 2
Material type and disposal method considered

Material type	Disposal method
Iron	Recycling (10% losses)
Fiberglass	Landfill (100%)
Oil	Combusted (100%)
Plastic PVC	Landfill (100%)
Other plastics	Combusted (100%)
Rubber	Combusted (100%)
Steel	Recycling (10% losses)
Copper	Recycling (5% losses)

The quality of the data is very varied, so we have sought to give more emphasis to those fields which generate a greater environmental impact, as ISO 14040 recommends [1].

3. Results of the LCA

Overall, the turbine unit has a greater environmental impact in the category corresponding to its effects on respiration, mainly due to substances of an inorganic source such as particle matter, sulphites and nitrates. Another aspect worthy of mention is the consumption of natural resources. This consumption is primarily reflected in the Fuel category.

Here are details of the main types of impact of each component in the various phases of the wind turbine's life cycle (see Fig. 3):

(a) Manufacturing stage: In the manufacturing phase of the wind turbine each component has been looked at separately. The manufacturing processes used in each case have been carefully analysed, as well as the amounts of raw material required and the energy used in their manufacture. With regard to the manufacturing phase, the impact categories with the greatest relevance are those related to inorganic respiration, climate change and the reduction of mineral resources. In the case of inorganic respiration, those components whose manufacture has the greatest impact are the foundation and the rotor. If we analyse the contribution of each raw material in the wind turbine manufacturing processes as a whole, prepreg is the element which has the greatest impact in the GWP category, while steel and copper are those which most affect the reduction in mineral resources.

(b) Transportation stage: To complete the transport phase, we have first looked at transport from the various component manufacturers to the assembly workshops of the company which builds the wind turbine. We have also included the transport of the wind turbine to its final emplacement in the wind farm. Transport processes include the impact of emissions caused by the extraction and production of fuel and the generation of energy from fuel during transport [27]. We have assumed 'tkm' as functional unit for transport. This unit is the transport of 1000 kg goods over 1 km [28]. Total transport calculated is 62,546 tkm with a theoretical energy consumption of 180,000 MJ. The impact categories most affected in this phase of the wind turbine's life cycle are inorganic respiration, climate change and acidification/eutrophication. The overall impact of this phase is not comparable with the manufacturing phase, as it has a very limited effect.

(c) Use stage: In this phase the categories which have the greatest impact are inorganic respiration and the reduction of mineral resources. This is basically due to the replacement of components during the time the turbine is in operation.

(d) Disposal stage: In the decommissioning phase we have assessed the materials directed to landfill such as concrete and prepreg [29]. The metals extracted are taken for recycling and the oil is incinerated. According to the decommissioning plan established for the wind farm, the foundations will not be removed but rather left in place and covered with a 30 cm layer of organic soil. In this way it is hoped that any contamination that would be caused by using heavy equipment, such as diggers, trucks, etc., can be avoided, although this entails a considerable loss of materials.

In Fig. 4 we can see the importance of the different impact categories for each of the main components of the wind turbine. For example, most of the environmental impact caused by the foundations is centred on the IR category. This is basically due to the environmental impact of the processes involved in making cement [30,31]. During this process the emission of particle matter into the atmosphere is considerable [32,33]. In the case of the rotor blade, the impact category with most relevance is that corresponding to fuel, with over 40% of the total. The rotor is to a large extent made up of the blades and the cone, elements containing a large amount of prepreg material, and this prepreg is the main culprit in the consumption of fossil fuels. With regard to this component, we can state that the phase which most needs to reduce its environmental impact is the manufacturing phase (see Fig. 5).

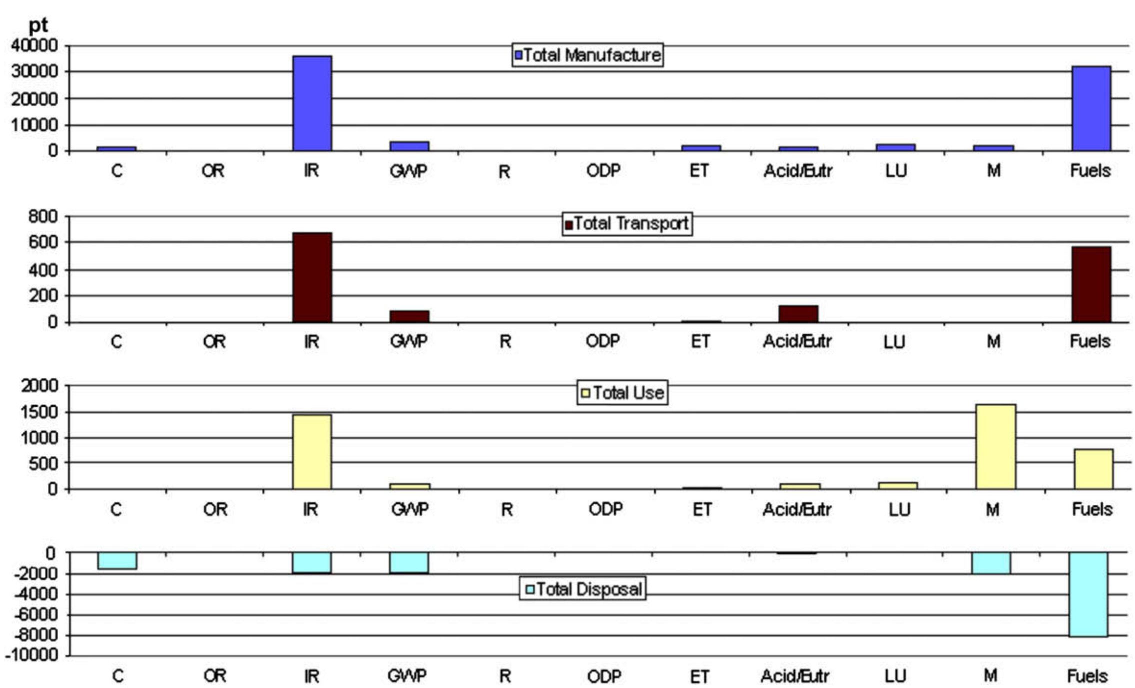

Fig. 3. Eco-profile of each life-cycle stage. Assessment method: Eco-Indicator 99. Results are given in Eco-points (pt).

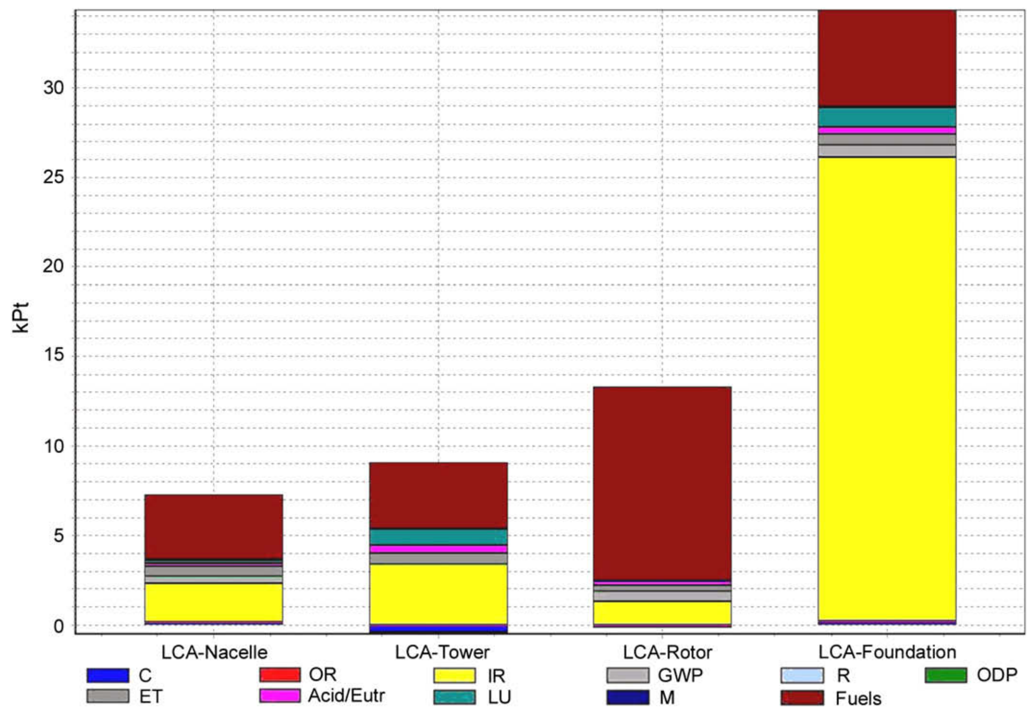

Fig. 4. Eco-profile of the four main components under study. Assessment method: Eco-Indicator 99. Results are given in kilo-Eco-points (kpt).

The manufacturing phase is also the one with the greatest impact on the environment in the case of the tower. Analysing this manufacturing phase in more detail we can see that most significant part of the environmental impact produced is centred on the quantity and type of materials used and in the welding process.

Finally, in Fig. 6 we can see the environmental impact of a wind turbine in terms of kWh produced during its entire life cycle. Considering the overall result of the turbine as a whole, the result obtained is close to one-thousandth of an Eco-Indicator point. Taking into account that the scale of the Eco-Indicator points considers the environmental impact of an average European citizen as being equal to 100 Eco-Indicator points [34], then the annual impact of a wind turbine can be roughly estimated as being close to four Eco-points.

4. Energy payback time of the wind farm

We have established as an average production of 2000 full-load hours per year [35]. In that way for a 2 MW rated turbine, the annual output can be estimated as being 4 GWh. This output of electrical energy allows us to reduce the levels of environmental impact, since we can reduce the need for energy production from the existing conventional power stations. In the case of IR, this reduction supposes the elimination of emissions into the air, basically SO_2 and NO_X. Moreover, GWP basically assesses the emissions of hydrocarbons and carbon dioxide into the atmosphere. If we consider that the lifetime of a wind turbine is estimated as being 20 years, then its benefits for the environment compared to other conventional sources of electricity are important. These calculations show that, during its lifetime, the wind turbine allows us to recover nearly 31 times the environmental contamination caused by its manufacture, start-up, operation and decommissioning.

The primary energy used in the production and disposal of materials comprising the wind turbine is 5782.25 GJ. Based on an estimated efficiency of 2000 equivalent full-load hours, the energy use is paid back in 0.40 year, or 2% of a 20 year lifetime. The efficiency used is rather low, but it is the same as the one used in the

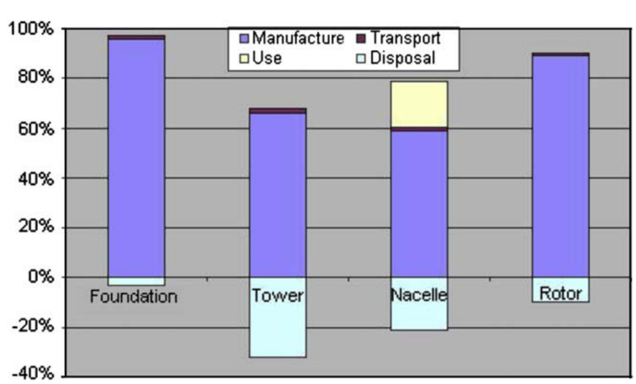

Fig. 5. Contribution of each life-cycle stage.

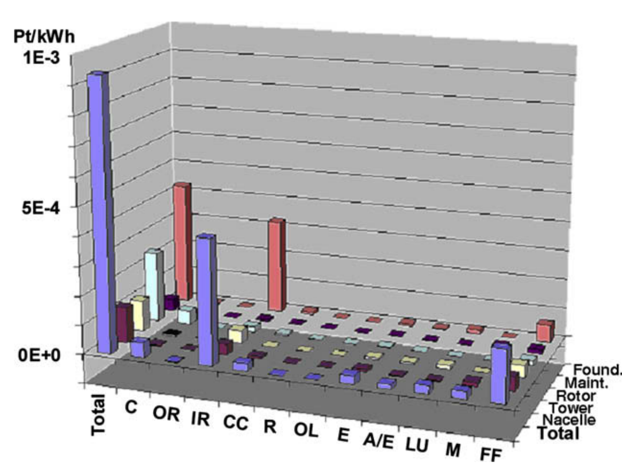

Fig. 6. Environmental impact of a wind turbine per kWh.

LCA model. For the purposes of this analysis, the "Eco-indicator '99" Life Cycle Impact Assessment methodology was adopted and the materials and procedures of a wind turbine production and utilization are evaluated. The overall result obtained was 65938.09 pts. In addition, contamination avoided by the generation of energy during the year is 108462.3 pts, so that the payback time for the contamination caused is 221.9 days, or less than 3.1% of a 20 year lifetime. In Table 3 we can see a detailed view of the turbine environmental impact which is avoided with the annual production of the wind turbine. The payback time has been obtained for each impact category defined by the Eco-Indicator 99. As is to be expected, energy output does not allow us to recover the impact associated with categories R, LU and M. Despite this, the payback time associated with the remaining categories still shows values of a maximum of 396.56 days.

5. The environmental impact of recycling end-of-life wind turbine

Another important aspect from the environmental point of view is to properly evaluate the decommissioning phase and the recycling of the turbine. In Table 4 we can see the values obtained for each of the phases of the recycling associated with the components defined in this study. Overall, the recycling processes studied allow us to significantly reduce the impact associated with the categories of Fuel, GWP, M, C and IR. Furthermore, the recycling results of the different components have been compared. The component whose recycling most favours the recuperation of environmental resources is the Tower, with 52% of the total general value recovered by all the processes of recycling. In second place comes the Nacelle, with 31% and finally the rotor and Foundation with 10% and 7%, respectively. If we look a little more closely at the impact categories, the most notable are those for Fuel, M, IR, GWP and C. The main components which affect these categories are the Tower and the Nacelle. In the case of the Tower it represents 63%, 46%, 62% and 44% in the categories of Fuel, IR, GWP and C, respectively. For its part, the Nacelle contributes 81% in category M.

6. Conclusions

From our study we can see that the foundation is the component which most affects the environment, particularly the cement, which is the main cause of the impact in the IR category. This fact points to the need to continue research into the manufacturing processes involved in preparing cement [36–38], in such a way that it would be possible to reduce its environmental impact. If we take into account that the effects on inorganic respiration as one of the main problems, it will be necessary to find a way of reducing air emissions, especially of particle matter, SO_2 and NO_X [31,39–41]. It is also interesting to look more closely into ways of recycling and reusing this material due to the important amount and its use in the construction of a wind turbine [42].

With regard to the tower, we should mention that the steel is almost completely recycled permitting a large part of the material used in its manufacture to be recovered. Wind turbines are reaching increasingly larger sizes of rotor diameter, and as a result the towers must always be higher and more robust so as to withstand the growing forces. Steel is the ideal material and it is difficult to replace it at the present time, and in addition it has a limited environmental impact although it is always possible to look for margins for improvement in the manufacturing processes of this raw material [43] or of the component as a whole, by trying to save on the energy used and reduce the amount of material thrown away.

The nacelle is the heart of the turbine and inside it carries the technology required for converting kinetic energy into electricity. Hence it is the most complex component, made up of a series of elements which are widely differing in nature. Each of these elements has its own associated technology and manufacturing processes, which certainly makes the study of the nacelle as a whole more complicated. The main environmental impact shown up by our study is that of the cost in copper. This metal has an enormous value and environmental impact [44,45], although it has the advantage of being recyclable [46]. The best solution is to try and reduce the amount used or replace it with another material with similar characteristics which will not reduce the generator's efficiency and improves the environmental impact.

From our study we can say that there is an undoubted environmental benefit in installing and starting up wind farms. But this does not mean that it is not necessary to continue investigating and raising our knowledge of this technology, especially if we consider the huge increase and expected future growth of wind power. One area of special relevance is the need to improve the environmental impact of the various manufacturing processes involved in making the turbine and its components. To reach this goal quickly and effectively it is vital to have the cooperation and interest of the various manufacturers. The manufacturers have to be able to assess the importance of using the results of the LCA to optimise their products [47] and to qualify for an eco-label [48].

Table 3
Payback time of wind turbine

Category	Turbine environmental impact (pt)	Environmental cost avoided by power generated in 1 year (pt)	Payback time (days)	% 20 Years
C	322.33	5221.82	22.53	0.31
OR	28.54	26.27	396.56	5.43
IR	28040.85	26482.92	386.47	5.29
GWP	2349.87	9134.37	93.90	1.29
R	16.40	0.00	Never	Never
ODP	7.11	6.60	393.42	5.39
ET	3156.05	5495.57	209.62	2.87
Acid./Eut.	2117.28	3758.59	205.61	2.82
LU	2951.07	0.00	Never	Never
M	46.32	0.00	Never	Never
Fuels	26902.26	58336.21	168.32	2.31

Table 4
Environmental impact prevented by recycling

	Nacelle recycling (kpt)	Rotor recycling (kpt)	Tower recycling (kpt)	Total (without foundation) (kpt)	Total with foundation (kpt)	Green energy (kpt)
C	−257	−1610	−686	−2553	−2740	−4380
OR	−0.807	−446	−1.92	−448.727	−446.847	−37.6
IR	−549	0	−907	−1456	−1180	−27,100
GWP	−403	−783	−1170	−2356	−2615	−9810
R	−2.43	−61.8	0	−64.23	−64	0
ODP	−0.274	−0.342	−0.509	−1.125	−0.983	−9.75
ET	−43.3	−0.0297	38.5	−4.8297	11	−3430
Acid./Eut.	−46.8	−34.6	−96.4	−177.8	−110	−2380
LU	−13	−0.482	0	−13.482	33.118	0
M	−1660	−30.4	−272	−1962.4	−2038	0
Fuels	−1820	−238	−5100	−7158	−8131	−50,200

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