First life cycle assessment of a French wind plant

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Wind power is an emerging renewable energy widely developed in many countries. Although several analyses have been conducted on the environmental impact of renewable energies, only a few life cycle assessment studies are available for wind plants. Consequently, Valorem developed a life cycle analysis model to evaluate, from a life cycle perspective, the potential environmental impacts associated with a French onshore wind plant comprised of five 3.0-MW wind turbines (...).

(...) The life cycle assessment (LCA) was based on data related to a French test wind plant. All stages of the life cycle (study, wind plant parts production, transportation, construction, wind plant operation including maintenance, disassembly and end-of-life treatment of the turbines) were analysed and sensitivity tests were carried out.
The wind plant construction stage was described in detail. In fact, this life cycle step is not adequately investigated in already published LCA studies. The second main innovation of this study is that the LCA was performed for a test wind plant using concrete towers.
The dismantling and end-of life stages are important for the life cycle analysis. As compared to other energy sources like nuclear energy, the advantage of wind energy is that the resulting waste is not toxic. However, composite wind turbine blades still present a waste management challenge. To estimate the importance of the end-of-life of composite blades, three different end-of-life scenarios were considered.
The influence of the wind plant's lifetime was also studied. In addition to the life cycle assessment, quantitative indicators such as energy payback time, energy intensity and CO_2 intensity were also calculated.

The use of wind energy to generate electricity is one of the most common technologies based on renewable energy sources.

In existing LCA studies related to wind energy [1-7], not all assessments follow the ISO standards [8-9], and some are more of energy and CO_2 assessments than full LCAs. Furthermore, no study has been found for the LCA of a wind plant using concrete towers.
Valorem contracted Rescoll to carry out an LCA for an onshore test wind plant comprised of five 3.0-MW wind turbines.
This study was prepared in accordance with the methodological requirements of the ISO 14040 and ISO 14044 standards [8-9].
The LCA methodology consists of four major steps:
1. Goal and scope definition.
2. Inventory analysis: collecting all the inputs and outputs of the system.
3. Impact assessment: evaluating the potential environmental impacts associated with these inputs and outputs.
4. Interpretation: evaluating the significance of the system's potential environmental impact.

The goal and scope stage outlines the rationale of the study, the boundary conditions, the data requirements and the assumptions made to analyse the system under consideration, and other similar technical specifications for the study.
This stage also includes the definition of a reference unit: all the inputs and outputs are related to this reference. It is called the functional unit, which provides a clear, full and definitive description of the product or service being investigated, enabling subsequent results to be interpreted correctly.

The second step is the inventory analysis, or life cycle inventory (LCI), which is primarily based on a system analysis treating the process chain as a sequence of sub-systems that exchange inputs and outputs. Hence, the LCI stage analyses the materials and energy used (inputs) as well as the products and by-products generated and the environmental releases in terms of non-retained emissions to specified environmental compartments and the waste to be treated (outputs) for the product system being studied.

The LCI data can be used on its own to understand the total emissions, waste and resource use associated with the material or the product being studied, to improve production or product performance; or be further analysed and interpreted to provide insights into the potential environmental impacts of the system (life cycle impact assessment and interpretation steps).

Goal, scope and background

The main objectives of this study were to:

- Deliver a rigorous and impartial environmental assessment of the wind plant in Pauillac, near Bordeaux, France.
- Describe the most favourable stages and the most impactful stages (from an environmental point of view) in order to identify optimization and improvement areas for technology and product development.
- Perform sensitivity analyses regarding the influence of different end-of-life treatments of composite blades and of the wind plant's lifetime on the environmental profile of the Pauillac wind plant.

Primary data were collected from Valorem and their suppliers [10-11]. When no primary data were available, secondary data based on literature [12-22] and validated by Valorem were used. These data were complemented by generic data available in the Ecoinvent database.

This wind plant is considered a test wind plant – the final wind turbines will be different from a technical point of view.

The system was simplified assuming that it was composed of identical turbines. All the data were collected in 2012. Indeed, as the wind plant is under development, it was not possible to base the study on a full year of operation.

It is important to be able to compare the potential environmental impacts associated with the electricity generated by a wind plant using specific turbines to other forms of electricity generation.

Functional unit and system boundaries

The functional unit of this LCA study was defined as 1 kWh of electricity delivered to the grid.

Figure 1 shows the life cycle stages considered to assess the environmental impact of the wind plant during its whole life cycle.

To assess the environmental impacts of the wind plant, the following indicators from the CML calculation method were selected: abiotic resource depletion, acidification potential, global warming potential, photochemical oxidation and eutrophication. Indicators proposed by the ReCiPe 2008 method were used to assess the damage to ecosystems caused by soil occupation and transformation.

The cumulative energy indicator was also used to quantify renewable and non-renewable energy consumption.

Impact assessment

This section describes the results of the evaluation of the wind plant environmental effects. The assessment was performed for the nine environmental impact indicators mentioned before (see Table 1).

Tab. I: Main results of the LCA

Impact category	Unit	Change
Cumulative energy demand	MJ	1.849E-01
Abiotic depletion	kg Sb eq	8.502E-05
Acidification	kg SO_2 eq	5.354E-05
Eutrophication	kg PO_4 eq	4.014E-05
Global warming potential	kg CO_2 eq	1.177E-02
Photochemical oxidation	kg C_2H_2 eq	3.985E-06
Agricultural land occupation	m^2a	1.935E-04
Urban land occupation	m^2a	1.447E-04
Natural land transformation	m^2	1.647E-06

The contribution of the wind plant's main life cycle stages to each impact category is shown in the following figure:

For the whole life cycle of the wind plant, the production stage is the most significant according to all the environmental impact indicators studied.

As shown in Fig. 3, the environmental analysis highlights a dominant incidence of the moving parts manufactured on eight of the nine indicators studied.

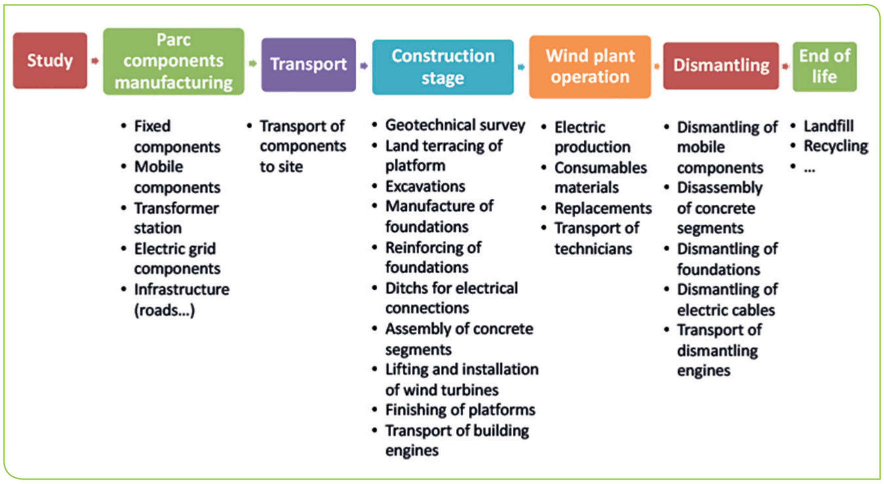

Fig. 1: Life cycle stages considered to assess the environmental impact of the wind plant

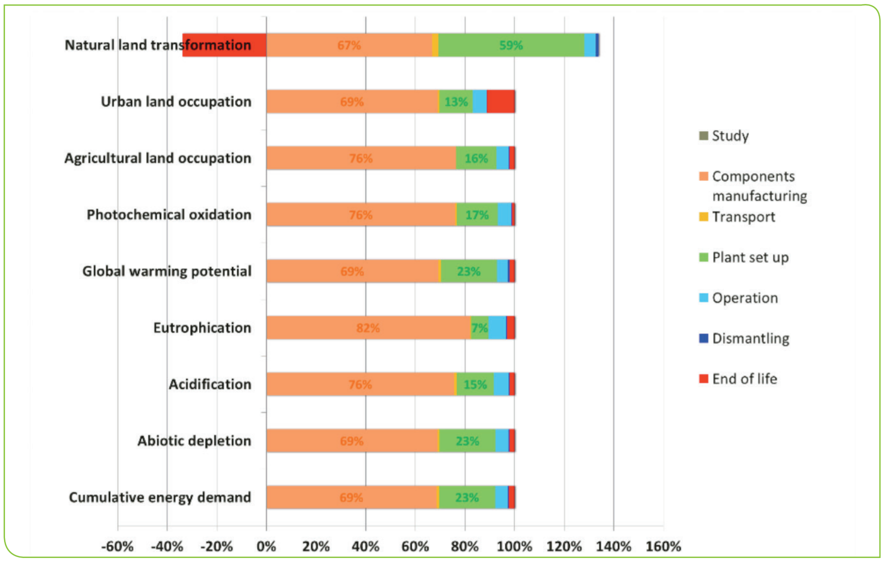

Fig. 2: Contribution of the main life cycle stages to the different impact categories

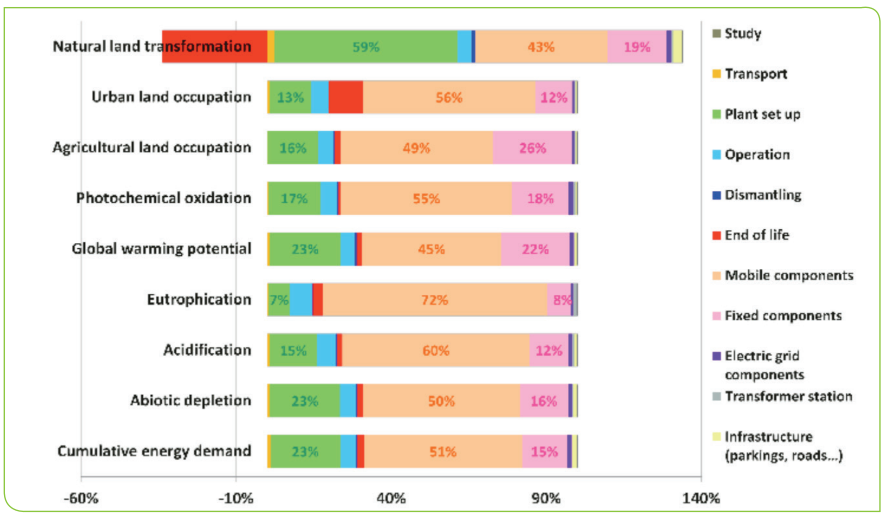

Fig. 3: Contribution of the main life cycle stages to impact categories where the production stage has been detailed

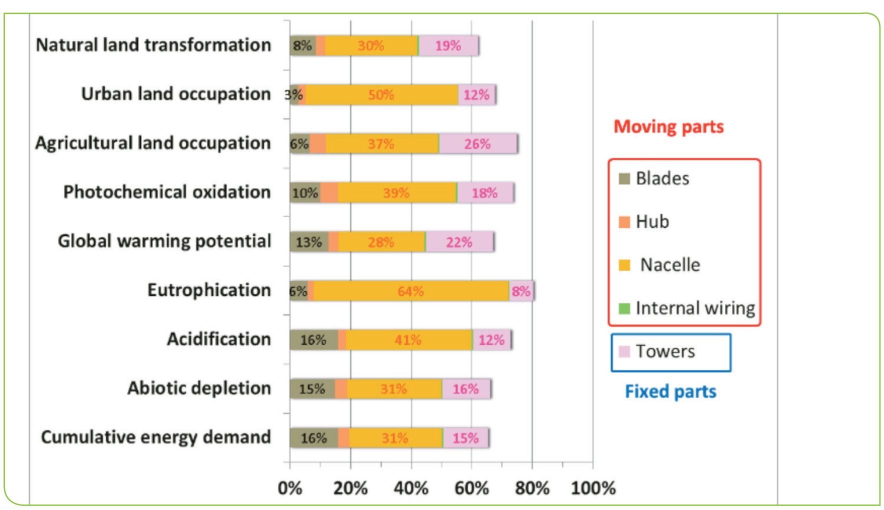

Fig. 4: Contribution of the manufacture of moving and fixed components to the wind plant's impact

More specifically, the nacelle has the highest incidence on moving parts impacts. This can be explained by the fact that the nacelle is the second heaviest component of the wind turbine and the most complex one in terms of composition.

The analysis of mass environmental impacts concentration (Fig. 4) shows that the blades have a significant contribution compared to the tower (non-moving part). The tower accounts for about 88% of the overall component weight while the blades make up about 3% (Table 2). This contribution is due to their composition. The blades consist of approximately 55% glass fibre and 34% epoxy. The introduction of new materials will probably be studied in order to reduce the environmental impacts [2].

Tab. 2: Mass percentage of the wind plant components

Component	Percentage (%)
Composite blades	2.94
Hub	2.07
Nacelle	6.79
Internal wiring	0.08
Towers	87.45
Electric grid components	0.16
Transformer station	0.51

Construction is the second most important stage of the whole life cycle (Fig. 5). More specifically, the foundations have a dominant incidence on 8 of the 9 environmental impact indicators, mainly because they are the heaviest part of the wind turbine (1,534 tons per foundation).

On the other hand, the study stage impacts of the wind plant's life cycle are insignificant (0.003 to 0.033%).
The component transportation stage from the plant site to the work site accounts for 0.2%-2.4% of the overall environmental impacts.

The operation stage accounts for 5.1-7.2% of all life cycle impacts and these impacts mainly come from component replace-

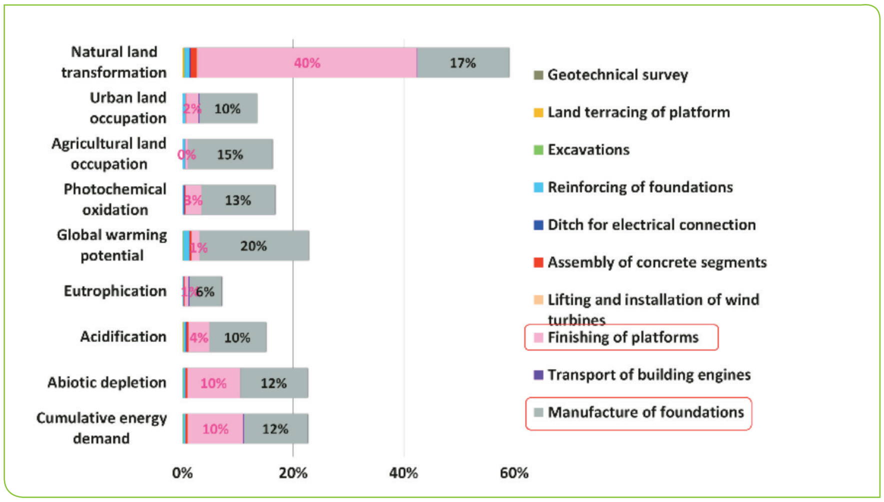

Fig. 5: Contribution of the construction stage to impact categories

ments.
The environmental burden of the dismantling stage is low: 0.2-1.1% of the whole life cycle impact. It should be noted that regarding the land transformation indicator, the dismantling stage accounts for -34% because the tower is made of concrete (Fig. 2 and Fig. 3). This negative value can be considered as an environmental benefit given that the landfill site is converted into forest land after its closure.

Sensitivity analysis

Sensitivity analysis is a systematic procedure for estimating the effects of the chosen methods and data on the outcome of a study.

Two sensitivity analyses were performed, varying two key parameters: the end-of-life scenario for the composite blades and the lifetime period.

Varying the blade end-of-life scenario

The analysis carried out in this section explores the impacts of different end-of-life scenarios for composite blades:

- Scenario 1: landfilling. This scenario considers the impacts resulting from landfilling of the components. This is the baseline scenario.
- Scenario 2: material recovery using a fine grinding process (from a few mm to 15 mm). The ground material can be reused for different purposes: paving concrete, road paving, composite boards for the building sector, insulation materials, reinforcement materials for thermoplastic materials, etc. This scenario takes into account the impacts resulting from the grinding process and gives "credit" for the burden avoided by reducing the primary production of gravel.
- Scenario 3: energy recovery from high calorific value waste. This scenario takes into account the burden resulting from blade incineration, giving "credit" for the avoided burden of an equivalent quantity of French electricity production.

The results of this sensitivity analysis are shown in Fig. 6.

As for the materials recovery scenario, most environmental indicators show a slight decrease compared to the baseline end-of-life scenario. In fact, the burden avoided by reducing the primary production of gravel is insignificant.

Regarding blade incineration in the energy recovery scenario, beneficial effects can be observed for 7 of the 9 impact indicators, especially for the cumulative energy demand category. In fact, the incineration of waste avoids the production of a certain amount of energy.

The impacts of this energy were counted as negative values considering that incineration makes a "profit" in the overall balance. However, the greenhouse effect is four times higher than the baseline scenario due to the greenhouse gas emitted during the incineration.

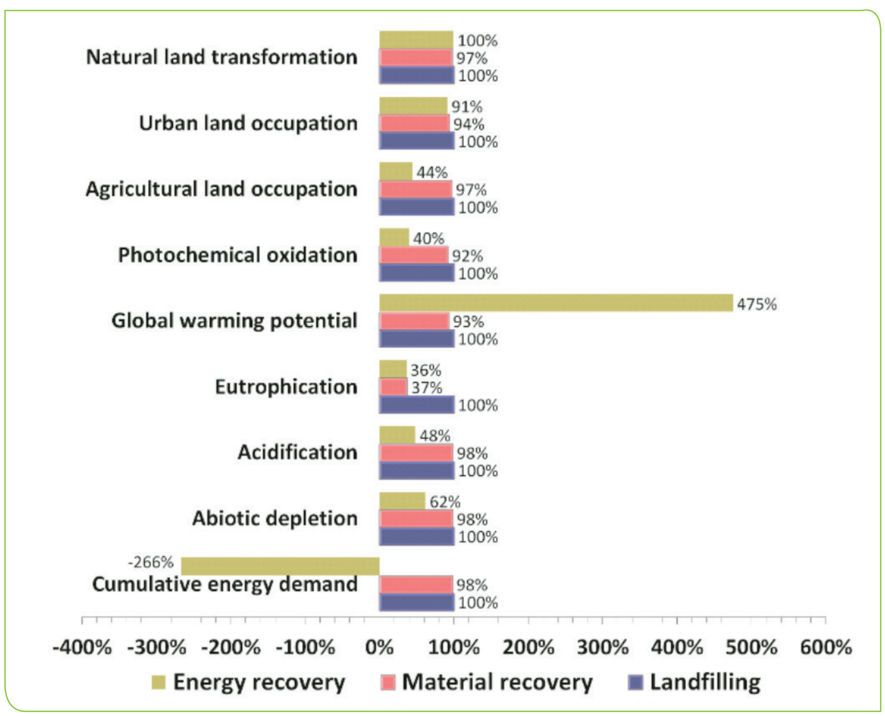

Fig. 6: Compared effects of different end-of-life scenarios for composite blades

Wind plant lifetime

The lifetime of the wind plant was assumed to be 20 years and was considered the baseline scenario. Based on its professional experience, Valorem indicated that this figure might reach up to 40 years.

Assuming that all the other variables remain fixed, increasing the lifetime of the wind plant will obviously result in lower emissions per kWh as the impacts associated with wind turbine manufacturing are amortised over a longer period of time.

However, the required maintenance and part replacements will be correlated with the lifetime of the wind plant (a longer lifetime involves more maintenance). Indeed, it was considered that the lifetime period of all the parts was twice as long, except the moving parts that still have a 20-year lifetime period.

The first results (for a wind plant lifetime period of 20 years) are compared to a 40-year wind plant in Table 3:

This assessment shows that the results decreased by 9-26% for all indicators. For five of the nine indicators studied, the overall results decreased by up to 20%.

Quantitative indicators

Tab. 3: Influence of lifetime on environmental impacts

Impact category	Unit	Lifetime		Change %
		20 years	40 years	
Cumulative energy demand	MJ	1.849E-01	1.458E-01	21
Abiotic depletion	kg Sb eq	8.502E-05	6.684E-05	21
Acidification	kg SO_2 eq	5.354E-05	4.489E-05	16
Eutrophication	kg PO_4 eq	4.014E-05	3.657E-05	9
Global warming potential	kg CO_2 eq	1.177E-02	8.874E-03	25
Photochemical oxidation	kg C_2H_2 eq	3.985E-06	3.213E-06	19
Agricultural land occupation	m²a	1.935E-04	1.496E-04	21
Urban land occupation	m²a	1.447E-04	1.185E-04	18
Natural land transformation	m²	1.647E-06	1.211E-06	26

When assessing the environmental performance of wind plants, an interesting aspect to consider is the point in time after which the environmental burden of the wind plant manufacture is outweighed by the environmental benefits of the renewable energy generated.

An energy balance was calculated to show the relationship between the energy requirement for the whole life cycle of the wind plant and its power output. The energy indicator calculated as explained before is called the energy payback time.

Another indicator widely used in practice to compare the environmental performance of wind plants is CO_2 intensity. This indicator is calculated as the equivalent amount of CO_2 emitted per kWh of electricity produced by the wind turbine throughout its life cycle.

Energy intensity, defined as the ratio of the amount of energy consumed and produced throughout the life cycle of the wind turbine, was also calculated.

The results for these indicators are shown in Table 4.

Conclusion

The main outcome of this study is an accurate and non-biased environmental assessment of the Pauillac wind plant in France. A special focus was placed on the construction stage since it directly concerns Valorem's activities. The life cycle assessment was used to identify the major impacts of the Pauillac wind plant throughout its whole life cycle.

As a main result, for each impact category investigated, the production stage of the wind plant's different components, more precisely the production of the moving parts, is the stage that

Tab. 4: Quantitative indicators

Lifetime	Indicator	Unit	Value
20 years	Energy payback time	Years	1.03
	Energy intensity	kWh used /kWh produced	0.051
	CO_2 intensity	Grams of CO_2 /kWh produced	11.77
40 years	Energy pay back time	kg C_2H_2 eq	0.81
	Energy intensity	m²a	0.040
	CO_2 intensity	m²a	8.87

generates the most impacts. It seems clear that research in new blade materials made from natural fibres and other new materials could be an interesting perspective to develop more sustainable wind turbines.

Secondary impacts come from the construction stage, with strong impacts related to the construction of the foundations for 8 of the 9 impact indicators. This is mainly due to the mass of the corresponding components.

The sensitivity analysis clearly highlights that the results are greatly influenced by the hypothesis of the wind plant lifetime. For instance, a lifetime increase from 20 to 40 years, taking into account the required maintenance and part replacements, reduces the impacts by 20% as the impacts related to the production of the different components depreciate over a longer period of time.

Three scenarios were considered for the end of life of the blades and no significant difference was observed between the material recovery and the landfill approaches. In the case of energy recovered from burning, there is an obvious positive impact on the cumulative energy demand; however the impact on global warming is 4 times higher compared to the reference scenario. In addition, the impacts linked to the occupation of agricultural fields, photochemical ozone layer production, eutrophication, acidification and depletion of abiotic resources are substantially

reduced.
Regarding quantitative indicators, the hypothesis for the lifetime of the plant showed a strong influence on the results since a 21% decrease is observed for the energy payback time indicator.

In consequence, this study is a valuable tool for Valorem-Valeol, for both their environmental impact management process and their continuous improvement. ■

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