LIFE CYCLE ASSESSMENT OF A FRENCH WIND PLANT

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Abstract:

Wind power is an emerging renewable energy extensively developed in many countries.

Although there are several analyses on the environmental impact of renewable energies, not many life cycle assessment studies exist for wind plants. Consequently, a Life Cycle Analysis model has been developed by VALOREM with the purpose of evaluating the potential environmental impacts associated with production of electricity from a French onshore wind plant comprised of five 3.0 MW wind turbines from a life cycle perspective.

The life cycle assessment (LCA) has been performed based on data related to a French test wind plant. All stages of life cycle (study stage, production of all parts of the wind plant, transportation, construction stage, wind plant operations including maintenance, disassembly and end of life treatment of turbines) have been analysed and sensitivity tests have been also carried out.

The wind plant construction stage has been 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, LCA was performed for a test wind plant based in concrete towers. As further as we know, this is the first LCA concerning this kind of towers made from self-compacting concrete and reinforced in steel. The results can be assumed as representative of the French context.

In addition to the life cycle assessment, quantitative indicators as payback time of energy, energy intensity and CO_2 intensity have been also calculated.

Keywords: Life cycle assessment LCA, wind plant, pay back time

1 Introduction

The employment of wind energy for electricity generation is one of the most diffused technologies for the exploitation of renewable energy sources.

Concerning existent LCA studies on wind energy [1-7], not all assessments claim to 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 regarding LCA of a wind plant based in concrete towers.

VALOREM has contracted RESCOLL to carry out a LCA of an onshore test wind plant comprised of five 3.0 MW wind turbines.

This study was prepared in accordance with the methodological stipulations of the following standards: ISO 14040 and ISO 14044 [8-9].

The LCA methodology consists of four major steps:

1. Goal and scope definition
2. Inventory analysis: collecting all inputs and outputs of the system.
3. Impact assessment: evaluating the potential environmental impacts associated with those inputs and outputs.
4. Interpretation: evaluating the significance of the potential environmental impact of the system.

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. The goal and scope stage also includes the definition of a reference unit: all the inputs and outputs are related to this reference. This 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, also called life cycle inventory (LCI), which is based primarily on systems 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 wastes to be treated (outputs) for the product system being studied.

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

2 Goal, scope and background

The main objectives of this study were:

- Deliver a rigorous and impartial environmental assessment of the wind plant in Pauillac, 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 the wind plant lifetime and of different end of life treatments of blades on the environmental profile of the Pauillac wind plant.

Primary data were collected from VALOREM and from their suppliers [10-11]. When primary data were not available, secondary data were based on literature [12-22] and were validated by VALOREM. These data have been complemented by generic data available in the Ecoinvent database.

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

We have simplified the system with the assumption that the system is composed of identical turbines. All data were collected during the year 2012. Indeed, as the wind plant is undergoing development, it was not possible to base the study on plant operation for a full year.

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

2.1 Functional unit and boundaries of the system

The functional unit of this LCA study was defined as:

1kWh of electricity delivered to the electrical grid.

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

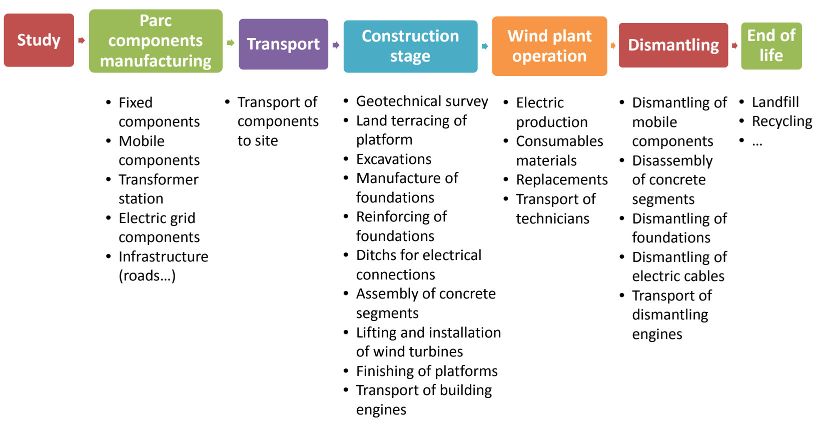

Figure 1: Life cycle stages considered for assessing the environmental impact of the wind plant.

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

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

3 Impact assessment

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

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

Table 1: Main results for the LCA.

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

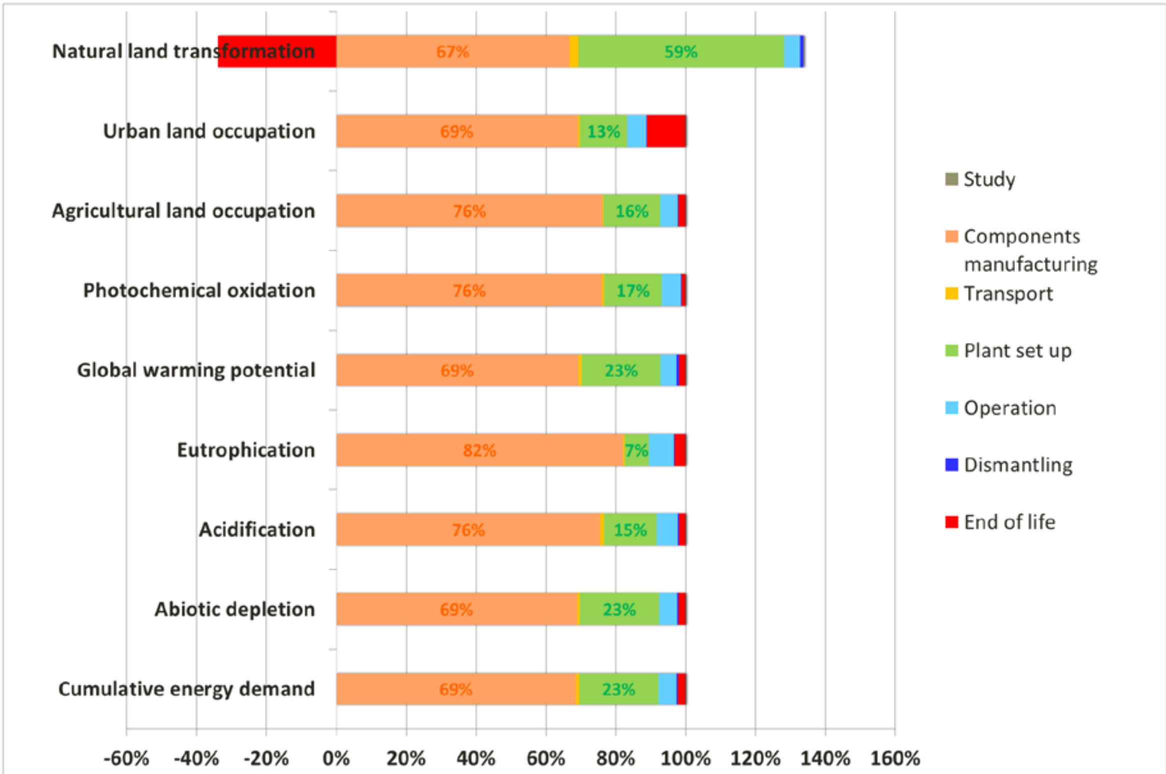

Figure 2: Contribution of the main life cycle stages to impact categories.

On the whole life cycle of the wind plant, the production stage is the most significant regarding all the environmental impact indicators studied.

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

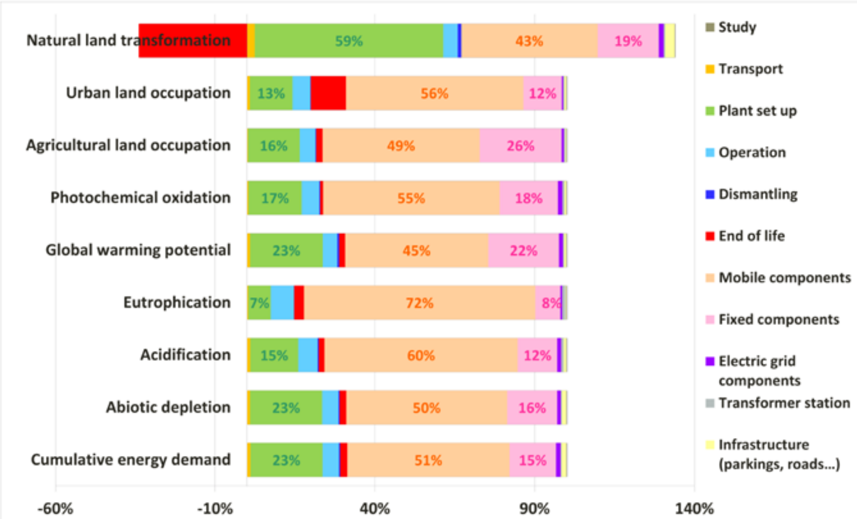

Figure 3: Contribution of the main life cycle stages to impact categories where the production stage has been detailed.

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

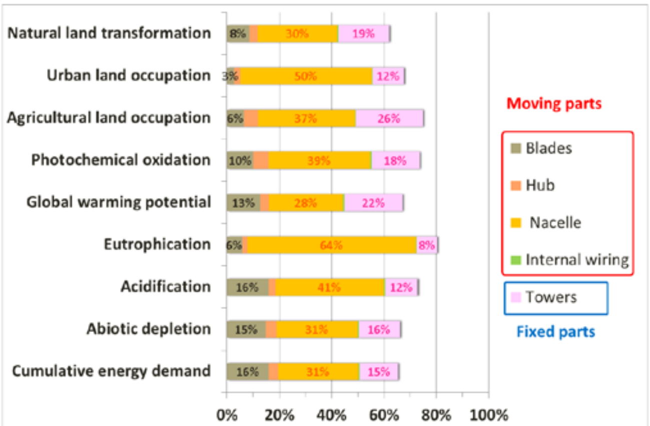

Figure 4: Contribution of manufacture of mobile and fixed components to impact of the wind plant.

Analysis of mass environmental impacts concentration (Figure 4) showed that blades have a significant contribution compared to the tower (non-moving parts).
The tower makes up ~88% of the overall component weight while blades make up ~3% (Table 2):

Component	Percentage (%)
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

Table 2: Mass percentage of the components of the wind plant.

The construction stage is the second most important of the whole life cycle (Figure 5). More specifically, foundations have a dominant incidence on 8 of 9 environmental impact indicators, mainly because they are the heaviest part of the wind turbine (1534 tons per foundation).

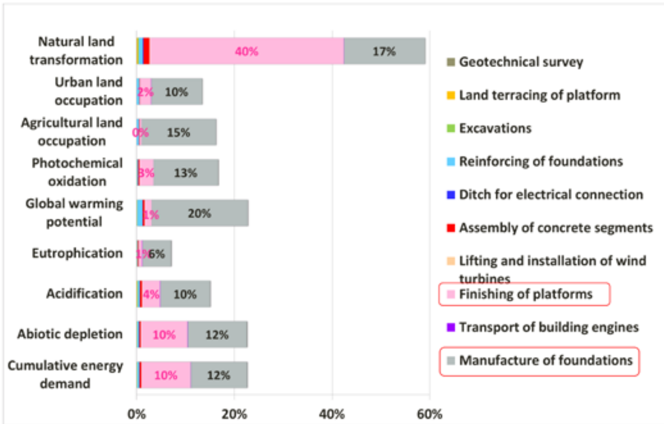

Figure 5: Contribution of the construction stage to impact categories.

On the other hand, the study stage impacts of the wind plant life cycle are insignificant (between 0.003 and 0.033%).

The components transport stage from their plant site to the work site represents between 0.2% and 2.4% of global environmental impacts.

The operation stage accounts for 5.1 to 7.2% of all life cycle impacts and these impacts mainly come from component replacements.

The environmental burdens of dismantling stage are low, 0.2% to 1.1% of the whole life cycle impact.

Finally, it should be noted that regarding the land transformation indicator, the dismantling stage accounts for -34%, due to the tower being made of concrete (Figure 2 and Figure 3). This negative value can actually be considered as a benefit to the environment, given that the landfill site is transformed into forest land after its closure.

4. Sensitivity analysis

This section details the sensitivity assessments that have been carried out in this study. Sensitivity analysis is a systematic procedure for estimating the effects on the outcome of a study of the chosen methods and data.

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

4.1 Wind plant lifetime

The lifetime of the wind plant was assumed to be 20 years and was considered the baseline scenario. Valorem has indicated based on professional experience that this figure might vary up to even 40 years.

Assuming all other variables remain fixed it is obvious that increasing the lifetime of the wind plant will lead to lower emissions per kWh as the impacts associated with manufacturing the wind turbines are amortised over a longer period of time.

However, the obligation of maintenance and replacement parts will be correlated with lifetime of the wind plant (a longer lifetime implies increased maintenance). Indeed, it was considered that all parts have a lifetime period two times longer, except moving parts that still have a 20-year lifetime period.

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

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	m^2a	1.935E-04	1.496E-04	23
Urban land occupation	m^2a	1.447E-04	1.185E-04	18
Natural land transformation	m^2	1.647E-06	1.211E-06	26

Table 3: Lifetime's influence on environmental impacts

This assessment shows that results for every indicator decreased between 9 and 26%. For five of the nine indicators studied, the decrease of global results was up to 20%.

4.2 Variation on end of life scenario of blades

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

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

Results regarding this sensibility analysis are shown in Figure 6:

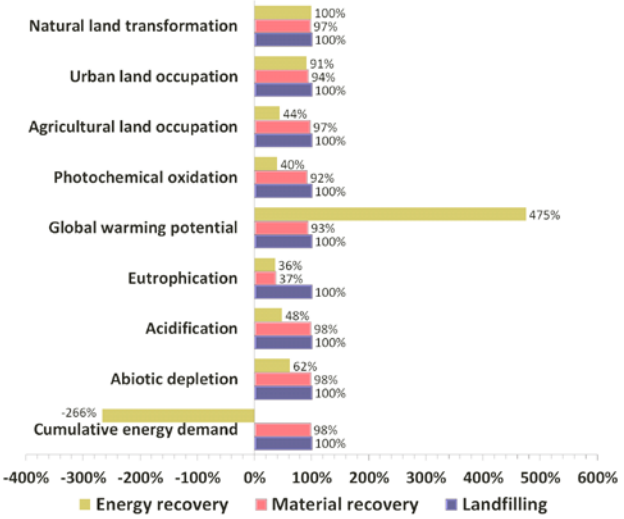

Figure 6: A comparison of the effects of considering different scenarios of blade end of life.

As for the materials recovery scenario, the majority of environmental indicators shows a slight decrease compared to the baseline end of life scenario. In fact, avoided burdens regarding 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 category of cumulative energy demand. In fact, the incineration of waste avoided to produce a certain amount of energy. The impacts of this energy have been counted in negative considering that incineration makes a profit in overall balance. However, the greenhouse effect is four times higher than the baseline scenario because of greenhouse gas emissions. This is due to emissions during incineration.

5. Quantitative indicators

An interesting aspect to consider when assessing the environmental performance of wind plants is the point in time after which the environmental burdens of producing the wind plant are outweighed by the environmental benefits of the renewable energy that is generated.

An energy balance was calculated showing the relationship between the energy requirement for the whole life cycle of the wind plant and the power output from the wind plant. The energy indicator calculated as explained previously is called Energy Payback Time.

Another indicator widely used in practice to compare the environmental performance of wind plants is the 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.

The Energy Intensity, defined as the ratio of the amount of energy consumed and the produced throughout the life cycle of the wind turbine, was also calcutated.
Results regarding these indicators are shown in table 4.

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 Payback Time	Years	0.81
	Energy Intensity	kWh used/kWh produced	0.040
	CO_2 Intensity	grams of CO_2/kWh produced	8.87

Table 4: Quantitative indicators.

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 realized on the construction stage since it directly concerns the activities of VALOREM. The use of the Life Cycle Assessment enabled the identification of 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 different components of the wind plant, and more precisely the production of the moving parts, is the stage that shows the most impacts.

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

The sensitivity analysis clearly highlighted that results are greatly influenced by the hypothesis of the wind plant life time. For instance, an increase of the life time from 20 to 40 years, taking into account the obligations for maintenance and replacement of parts, leads to a 20% decrease of the impacts as the impacts linked to the production of the different components depreciate over a longer period of time.

For the end of life, three scenarios were considered for the blades and no significant difference was observed between the materials recovery and the landfill approach. In the case of energy recovered from burning, there is an evident positive impact on the cumulative energy demand, however impact on global warming is 4 times higher compared to the reference scenario. In addition, 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 on the life time of the plant showed a strong influence on the results since a decrease of 21% is observed for the Energy Payback Time indicator.

In consequence, this study is a valuable tool for VALOREM-VALEOL: for their process of managing environmental impacts and their continuous improvement.

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