Assessment of the Environmental Impacts of a Wind Farm in Central Greece during its Life Cycle

Konstadinos Abeliotis*‡, Despina Pactiti*

*School of Environment, Geography and Applied Economics, Harokopio University, Athens, Greece

(kabeli@hua.gr; dpactiti@outlook.com.gr)

‡Corresponding Author; El. Venizelou 70, 17671 Athens, Greece, Tel: +30 210 95 49 363,

Fax: +30 210 95 77 050, kabeli@hua.gr

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Abstract- Wind energy installations in Greece are increasing rapidly as a means to achieve the national goal for increasing the renewables' share in the country's energy balance. However, wind farm installations are not impact free from the environmental standpoint. The present study examines the cradle-to-grave impacts of a wind farm in central Greece composed of four, 850 MW each, wind turbines. Life cycle inventory data were obtained from secondary sources and the CML 2 baseline 2000 ready-made method was utilized for the environmental assessment in nine impact categories. The results indicate an intensity index of 4.1 kg CO_2 eq. per MWh along with an energy payback time of 7 months. Towers, nacelles and the foundations of the turbines are the wind farm components that cause the most environmental impacts. However, key impact categories associated with energy, such as alteration of local climate, killing of birds and bats, noise and visual impact are not assessed. Despite the limitation of the study, the major conclusion is that electricity generation from wind power is environmentally preferable compared to the current electricity generation mix in Greece.

Keywords Life cycle assessment; Wind energy; Greece.

1. Introduction

The advantages related to climate change mitigation of renewable energy technologies are well documented [1-4]. However, these technologies are not impact-free, from the environmental standpoint, since they consume raw materials and energy for their manufacturing, transportation, installation, maintenance, dismantling and disposal. Thus, electricity generation from renewable sources is "not clean, but cleaner", compared to conventional sources [5]. The holistic methodology of life cycle assessment (LCA) sheds new light in the assessment of the environmental impacts of renewable energy technologies and on how these impacts compare to the respective generated from conventional, i.e. fossil fuel based, technologies. LCA is one, among others, assessment methods used in the study of various life cycle stages of the wind energy electricity generation [2].

More specifically, LCA has been applied for the assessment of various issues in wind power electricity generation. For instance, a research group from Spain studied a 2 MW onshore wind turbine and also performed and LCA sensitivity analysis on the same turbine [6-8]. Guezuraga et al. [1] compare two different 2 MW wind turbines while Tremeac and Meunier [9] compare two wind turbines with considerably different capacities, one of 4.5 MW and one of 250 W. Crawford [10] studies, also, the effect of the size of the wind turbines on their life cycle energy and greenhouse emissions. Zhong et al. [11] compare a wind turbine with a polycrystalline photovoltaic module while Raadal et al. [2] compare wind power and hydro power. Ardente et al. [5] study wind farms in Italy while Wagner et al. [12] and Weinzettel et al. [13] study floating offshore wind turbines by LCA means. Recently, a study was published referring to wind turbines positioning in Greece utilising LCA [13]. In terms of the size of wind turbines, LCA reveals that the larger the rated output power of the wind turbine, the lower the CO_2 emissions per KWh generated [2].

Regarding the impact indicators utilized for the assessment of the wind power electricity generation in the aforementioned studies, there are two approaches: the first one, used for example by Guezuraga et al. [1] and Ardente et al. [5], utilizes only the energy payback time (expressed in months) and global warming potential (expressed in CO_2 eq.). Actually, energy payback time and CO_2 emissions are the most commonly used indicators [10] to compare wind energy electricity generation to conventional fossil sources. However, this kind of analysis is termed as "energy analysis" [2]. Moreover, [10] advises that while energy payback time and greenhouse emissions are useful indicators of the environmental impacts, other factors should also be considered. Thus, the second approach, used for example by Martínez et al. [6, 7], Zhong et al. [11], and Weinzettel et al. [14], engages full-blown life cycle impact assessment indicators.

Wind energy installations are increasing rapidly in Greece. Overall, 1864.6 MW were installed till the end of 2013 [15]. However, all wind turbines are imported in Greece since there is no domestic production. This fact is interesting enough, since transportation puts an environmental burden on the wind power generation. Thus, the aim of this study is the presentation of the environmental LCA of an onshore wind farm located in central Greece.

2. Goal and scope definition

There are four steps in an LCA: goal and scope definition, inventory analysis, impact assessment and interpretation [16]. The goal of this research is the LCA of an onshore wind farm located in central Greece, consisting of four 850 MW turbines. The wind farm is currently in the licensing phase, i.e. it is not installed and operating. It is located at the "Patoma" location of the municipality of Tempi in central Greece. The wind farm consists of four turbines (three-bladed G-58 model of the Gamesa A/S), 850 KW rated capacity each. The wind farm site is located within the limits of the Ossa aesthetic forest (NATURA 2000 Special Area of Conservation 142003), but outside its priority habitats; the small turbine size has been selected for better integration in the natural environment and for being the most suitable for the wind potential of this area. The annual gross electricity generation of the wind farm is estimated at 10,600 MWh.

The scope of the assessment includes manufacturing and transportation of the turbine parts, the works for the foundation of the turbines, maintenance of the wind farm, its dismantling and the end-of-life management (recycling and disposal) of the farm components. The functional unit of the assessment is defined as "1 MWh of generated electricity from the wind farm".

3. Life cycle inventory

The farm is examined within its natural, geographical and time boundaries. Regarding the natural limits, the system starts from the extraction of raw material for the manufacturing of the turbine parts and ends with the final disposal of these parts. The geographical limits start from Spain, where manufacturing of the turbine parts takes place, and end in central Greece which is the place where the turbines are installed, operating, maintained and finally disposed off. Finally, the time limits of the system are extended within a time span of 20 years, as suggested by Martínez et al. [6] and Weinzettel et al. [14]. The system boundary of the present study is summarised in Fig. 1.

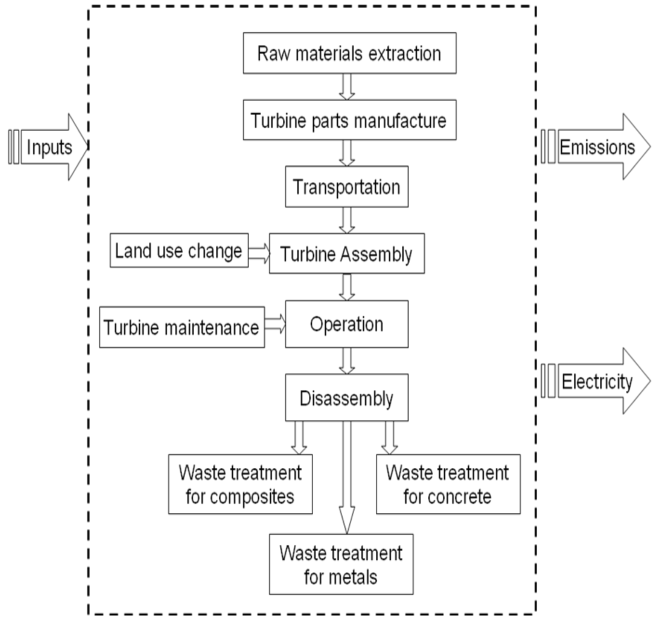

Fig. 1. System boundary

The turbine parts are transported to Greece by ship, from the port of Barcelona to the port of Volos, and from there by road to the wind farm site. Environmentally speaking, this is the optimal transportation route based on the recommendation that transportation of wind turbines should be kept to a minimum since it adds significantly to the environmental impacts [1, 9]. After 20 years of operation, the turbines are dismantled. Those of their parts that can be recycled are moved to the nearby recycling facility while their foundation is buried in the location of the farm. Recycling of the recyclable turbine parts, at the end of their life time, should be performed correctly, if environmental impact is to be minimized [9, 14]. The life cycle inventory of the wind farm is presented in Table 1.

Table 1. Life cycle inventory for the wind farm (adapted from Crawford [10])

Turbine part	Material	Weight (t)
Foundation	Concrete	1,190
	Cast iron	46
Tower	Stainless steel	180
Rotor	Fiberglass	24
	Stainless steel	24
Nacelle	Copper	4.2
	Aluminum	2.4
	Fiberglass	0.8
	Stainless steel	80.8

Technical data for the G-58 wind turbine were compiled from relevant internet sources [17]. Data were also extracted from published articles in refereed journals and the energy assessment study of the owner of the wind farm. Google Earth and Toponavigator Pro were used for the estimation of the transportation distances. SimaPro 5.1 was the software used for the LCA modelling.

The main assumptions engaged for the compilation of the life cycle inventory are:

1. The life span of the wind farm is 20 years, with an annual electricity generation of 10,600 MWh.
2. Each turbine consists of the rotor, the nacelle, and the tower. The rotor (including hub) weighs 12t; 6t of those are fibre glass and the remaining 6t are steel. The nacelle (without rotor and hub) of the turbine weighs 22 t. Of those, 20.2t are steel, 1t is copper, 0.6t is aluminium and 0.2t are high density polyethylene. Each tower weighs 45t of steel. Table 1 presents the life cycle inventory data for the entire wind farm.
3. The turbine parts via the port of Barcelona are transported to the port of Volos by ship for a distance of 3,287 km. The total weight for each turbine is 80 t [17]. The wind farm consists of four wind turbines, thus the total weight transported from Barcelona to Volos equals 320 t, and the total transportation load is 1,051,840 tkm.
4. The parts of the wind turbines are then transported from Volos to Patoma, i.e. the wind farm site, by 40t trucks for a distance of 100 km. Thus the transportation workload is calculated as 32,000 tkm.
5. The area occupied by the wind farm is 2,000 m^2. This includes: new forest roads, the control centre and the area for the foundation of the turbine towers (375 m^2 for each turbine).
6. The environmental loads associated with the auxiliary materials required for the construction and operation of the control centre are not included. Moreover, the widening of existing roads and the opening of new roads is also not included.
7. An excavation of 2.5 m in depth by 8 m in diameter is required for each tower, along with 125 m^3 of concrete along with 11.5 tons of iron. Properties of concrete were retrieved from Lydon [18]. The total excavation work load is 500 m^3, performed by an excavation hydraulic digger.
8. Turbine maintenance includes replacement of the lubricating oils every second year. During the life time of the wind farm 1,500 kg of lubricating oil are required for all four turbines. No other components will be replaced during the life span of the turbines.
9. Once the life span of the wind farm is reached, the wind turbines will be dismantled: 90% of the recyclable materials will be recycled while the remaining 10% will end up in the landfill. Both the recycling facility and the landfill are located 15 km west of the wind farm location. Transportation of the turbine parts, to either the recycling facility or the landfill, takes place via 40 t trucks. The metallic parts of the turbines are recycled by 90% while all the plastics end up in the landfill. Concrete and steel utilized for the foundation of the turbines are buried in the wind farm site, i.e. there is no transportation stage involved.
10. Electricity generation is the single function of the wind farm; thus no allocation of the impacts is performed.
11. Grid losses and infrastructure related to the grid were excluded from the assessment. The available medium voltage infrastructure of the area will be utilized for the electricity transfer.

4. Life cycle impact assessment

The ready-made impact assessment method used was CML 2 baseline 2000 which is well-established in the field of wind energy LCA [7, 14]. The method's impact category indicators, included in our assessment, are: abiotic depletion factor, stratospheric ozone depletion potential, global warming potential (100 years time horizon), fresh water aquatic ecotoxicity potential, terrestrial ecotoxicity potential, human toxicity potential, photochemical ozone creation potential, acidification potential, and eutrophication potential. These categories are reported to be among the most relevant to wind energy electricity generation [6, 7, 11, 14]. The marine aquatic ecotoxicity impact category was excluded from our assessment, based on relevant recommendations [14, 19]. Table 2 presents the characterization results of the impact assessment in the aforementioned nine impact categories for the wind farm.

5. Discussion

The relative contribution, per impact category, of each one of the wind farm's life cycle stages is presented graphically in Fig. 2. More specifically, four main components of the turbines are considered, namely, tower, rotor, nacelle, and foundation in addition to the life cycle stages of maintenance, transport and end-of-life management.

On the abiotic depletion and global warming potential (100 years horizon), the towers have the greatest contribution followed by the foundations and the nacelles (see Fig. 2). For the ozone layer depletion, foundations have the greatest contribution followed by the towers and the nacelles. Regarding the human toxicity and the freshwater aquatic ecotoxicity, towers have the greatest contribution, followed by nacelles. For the terrestrial ecotoxicity, foundations are the major contributors to the environmental impacts followed by the towers and the nacelles. For the photochemical oxidation, nacelles are the major contributors to the impacts followed by towers and foundations.

For acidification, nacelles have the greatest impact, followed by the foundations and the towers. Finally, for eutrophication, towers have the greatest contribution followed by foundations and nacelles.

As already mentioned in the introductory section, a very common impact assessment indicator in wind energy LCAs is the energy payback time. The CML 2 baseline 2000 impact assessment methodology does not include such an indicator. Thus, the calculation of the energy payback time is

Table 2. Life cycle impact assessment indicator values

Impact category	Unit (kg)	Tower	Rotor	Nacelle	Foundation	Maintenance	Transport	End-of-life	Total
Abiotic depletion	Sb eq.	3,960	132	2,170	2,340	32.9	93.4	-5,010	3,720
Global warming (GWP100)	CO_2 eq.	398,000	12,300	242,000	276,000	405	14,000	-70,200	872,000
Ozone layer depletion	CFC11 eq.	0.107	14.8E-5	0.0639	0.108	0	0.0193	0.0261	0.325
Human toxicity	1,4DB eq.	381,000	742	266,000	147,000	0.166	8,110	40,700	843,000
Fresh water ecotoxicity	1,4DB eq.	49,500	126	25,100	22,100	0.00549	789	11,400	109,000
Terrestrial ecotoxicity	1,4DB eq.	1,570	7.05	879	1,640	8.63E-24	184	546	4,830
Photochemical oxidation	C_2H_2	242	2.95	252	111	0.0827	12.5	-89.9	531
Acidification	SO_2 eq.	1,640	69.9	4,330	1,810	1.98	305	101	8,260
Eutrophication	PO_4^{---} eq.	99.4	0.171	51.3	67.4	0.00657	19.2	3.84	241

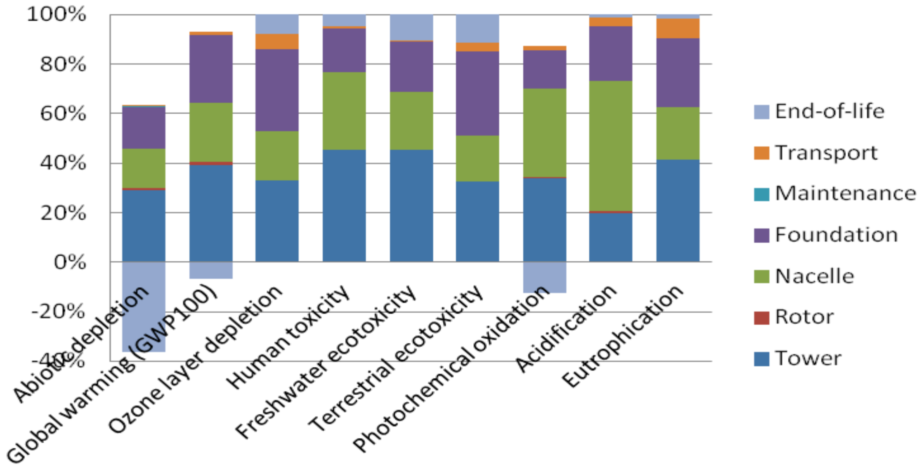

Fig. 2. Relative contribution of major wind turbine components per impact category

performed manually and is based on the inventory Table 1 and the energy content data for the various wind turbine assembly materials presented in Kabir et al. [20]. The energy payback time of the wind farm under consideration is estimated to be seven months.

Finally, as shown in Table 2, the components of the wind turbines, i.e. nacelles and towers, are contributing from 70 to more than 80% to every impact category. Installation of the turbines (i.e. foundation) is the next life cycle stage that contributes the most to the environmental impacts. Transportation of the wind turbine parts and maintenance of the wind farm have negligible effect on the nine impact categories. Finally, the end-of-life stage of the wind farm has a positive environmental impact (indicated by negative numbers in Table 2) on the abiotic depletion, global warming and photochemical oxidation impact categories, mainly due to the recycling of the metallic parts of the turbines.

The assessment results indicate that foundation of the turbines causes the most environmental impact in four categories, namely global warming, ozone layer depletion, terrestrial ecotoxicity and eutrophication. Towers cause the major environmental burden on the abiotic resources depletion, human toxicity, freshwater aquatic ecotoxicity, and photochemical oxidation. Finally, nacelle materials cause the major impact in acidification. These findings are in very good agreement with the results of Guezuraga et al. [1], which report that the main environmental (~85%) impacts for a wind turbine result from its production. Therefore, in order to reduce the environmental impacts of onshore wind farms, a shift towards turbines with a larger share of concrete and a smaller share of stainless steel is desired [1].

The impact assessment results for global warming potential (see Table 2) indicate an intensity index, as defined by [9], of 4.1 kg CO_2 eq. per MWh which is close to the values reported in a recent literature review [2] and lower than those reported recently for onshore wind energy generation in Greece by Angelakoglou et al. [13] and Theodosiou et al. [21]. Also, the calculated energy payback time of the present study, i.e. 7 months, is in very good agreement with the results reported in the literature, i.e. that the energy payback time for wind turbines, of any size, is less than a year [6, 10]. However, despite the agreement with other published literature, it is very clear that the presently available life cycle impact assessment models do not take into account major environmental impacts associated with wind energy such as alteration of local climate [22, 23], killing of birds and bats [24-26], noise [24-26] and visual impact [24-26]. Note that the wind farm examined by the present study is very close to an aesthetic forest. Therefore, visual impacts or the killing of birds maybe very significant. For these neglected impact categories, new assessment indices should be developed and incorporated into the current models.

6. Conclusions

Wind energy is a global key player towards the substitution of conventional fossil-based electricity generation technologies. The LCA has been applied to address the environmental impacts of wind energy generation from a wind farm located in central Greece. An intensity index of 4.1 kg CO_2 eq. per MWh has been calculated along with an energy payback time of seven months. The results indicate that the generation of electricity from wind power is definitely environmentally favourable compared to the current electricity generation mix in Greece. However, this study also reveals the generic limitations that LCA has regarding the complete assessment of life cycle impacts of wind energy. Thus, as a final remark, more research is required in terms of LCA for the environmental assessment of renewable energy generation in Greece and globally.

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