

## COMPARISON ANALYSIS OF BLADE LIFE CYCLES OF LAND-BASED AND OFFSHORE WIND POWER PLANTS

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### ABSTRACT

*In recent years, the offshore wind power industry has been growing dynamically. A key element which decides upon power output of a wind power plant is blades. They are most frequently produced from polymers – laminates with epoxy resins and fiberglass. In the near future, when the blade life cycles are over, large amounts of waste material of this type will have to be reused. This paper presents a comparison analysis of the impact of particular material existence cycle stages of land-based and offshore wind power plant blades on the environment. Two wind power plant blades, of about 49 m in length each, were examined using the LCA method, the programme SimaPro, and Ekowskażnik 99 modelling (phase LCIA).*

**Keywords:** life cycle assessment (LCA), wind power plant blades, post-consumer reuse of materials, offshore wind power plants, Ekowskażnik 99

### INTRODUCTION

The comparison analysis of blade life cycles of land-based and offshore wind power plants should assess, on the one hand, the amount of potential resources of waste materials of this type and, on the other hand, their systematic growth in time due to, for instance, reaching the assumed durability.

Among the available renewable energy sources, particular attention should be given to wind power plants (Haapala i inni, 2014). Year by year, the power of the installed wind power plants is steadily increasing. According to Global Wind Energy Council (GWEC) and EurObserv'ER, the total installed power capacity of wind turbines reached approximately 500 GW in year 2016 (Fig. 1) and is expected to reach nearly 800 GW in year 2020 (GWEC, 2016).

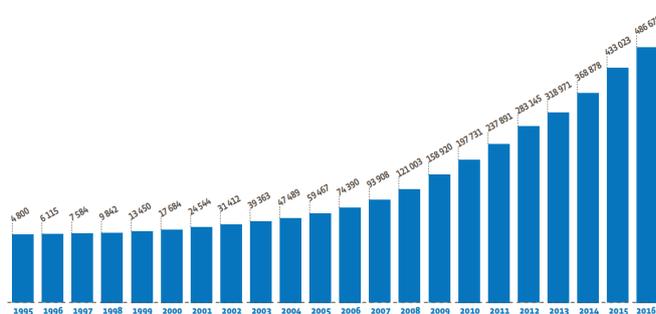


Fig. 1. Total cumulative wind power capacity installed worldwide since 1995 MW (\* Estimate Source: EurObserv'ER 2017)

It is expected that, following the technological progress, the offshore wind power plants will be a significant part of

world power industry. A good example of profitable and cost-efficient investments in this area can be offshore wind farms in Europe (Denmark, UK) and North America (Breton et al., 2009).

The wind power industry is widely regarded as environment friendly, as wind energy conversion to electric power is not accompanied by emission of toxic gases nor pollutants. In year 2016, the amount of CO<sub>2</sub> emitted to the atmosphere exceeded 4 Gt. However, there is no technical object which is free from impact on the environment. The wind power plant existence cycle influences the environment mostly at the manufacturing stage, but also in the post-consumer reuse phase (on a landfill site or via recycling). From the point of view of environment friendly designing, an important issue is analysing the impact of the used materials on the environment and forms of their post-consumer reuse for the object to have minimal negative impact on the environment. The construction element manufacturing process itself is characterised by high power consumption. It is therefore justified to analyse the impact of wind turbine existence cycle on the environment (Davidsson et al., 2012).

Rapid development in the number of wind power plants has been a motivation for many scientists to identify environmental profits resulting from the existence of wind power plants. The life cycle analysis is a method which makes it possible to determine the impact of the existence cycle of a selected technical object on the environment. The research studies carried out to date suggest that the energy put into the wind power plant life cycle is returned after ten to twenty months of power plant operation. For offshore wind power plants this assessment is even more satisfying due to higher wind speeds and higher annual power output (Crawford, 2009).

In energy terms, it is offshore wind turbines with large areas swept by blades which are most profitable. In this context, blades can be considered a crucial element which decides upon power output of the wind power plant. Consequently, proper blade modelling and manufacturing is an important issue. A properly designed blade, of relatively small weight, makes it possible to limit requirements concerning the structure of hub and tower, which results in the decrease of wind power plant production and operation costs (Świtoński et al., 2007) (Piasecka et al., 2015).

**The article aims at** adopting the criteria and analysing the amount, type and potential of used materials, as well as energy consumption, at each existence stage of land-based and offshore wind power plant blades. The analysis will also include environmental profits and expenditures, and harmful actions of dominating life cycle areas/phases of the adopted blade structures.

## STRUCTURE OF LAND-BASED AND OFFSHORE WIND POWER PLANT BLADE

Due to the performed function and operating conditions, the blades of an offshore wind power plant should have small weight, high durability, and resistance to changing atmospheric conditions and corrosion. Therefore, of high importance is proper selection of construction materials for blades and their structure, which will then affect the way of post-consumer reuse of elements and materials composing the blade (Shokrieh et al., 2010), (Kong et al., 2005), (Świtoński et al., 2007).

A typical wind power plant blade consists of three components, which are: outer shell, vertical spars, and root joint (Fig. 2) (Shokrieh et al., 2010).

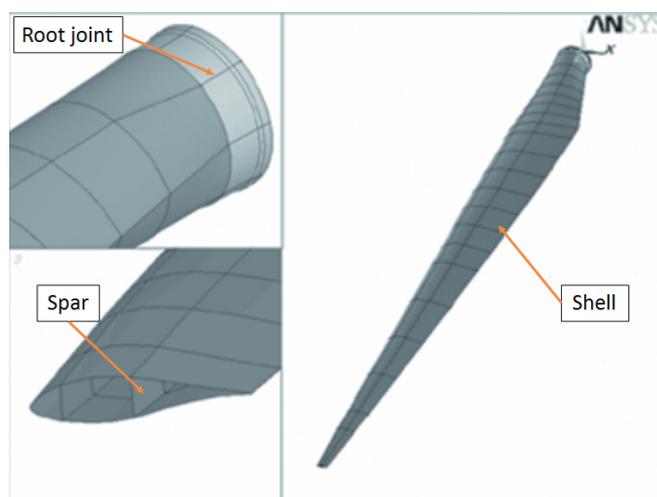


Fig. 2. Basic structural components of wind power plant blade (Shokrieh et al., 2010)

Blades of commercial wind power plants are made of composite materials (laminates), balsa wood, and steel. Each blade component plays different function and is made of different construction materials. The outer shell is produced from composites, plastics and balsa wood, using the lamination method. The core of the laminate is made of balsa or polyvinyl chloride (PVC) and fiberglass, while epoxide, polyester, or vinyl ester resins are used as warp. These materials are relatively light and robust, which provides good opportunity for maximal use of the lift generated on the blades. The blade surface is protected using gelcoats and polyurethanes. Protecting layers for offshore wind turbine blades are thicker than those for land-based turbine blades, due to the nature of marine environment (high humidity, salinity) which contributes to weakening of outer shells. Front blade edges are covered with thermoplastic foils or special paints. Figure 3 shows the blade structure cross section, with marked elements made of composites (Shokrieh et al., 2010), (Xiaohui et al., 2013) (Composite recycling: Characterizing end of life wind turbine blade material, 2014) (Kasner et al., 2015) (Kong et al., 2005).

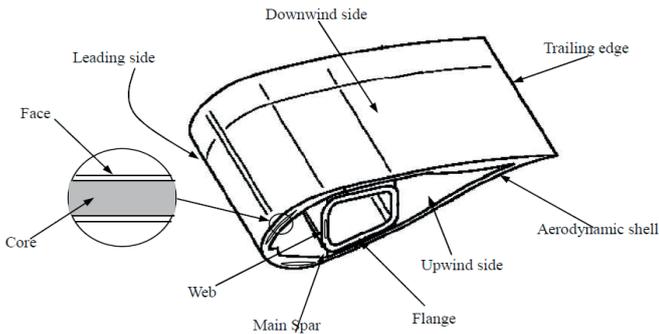


Fig. 3. Wind power plant blade structure (cross section) (Xiaohui, et al., 2013)

The task of the wind turbine suspension tower is to carry forces and stresses coming from different sources, therefore it is constructed from durable laminate composites made of carbon fibre and fiberglass, as well as resins (most frequently epoxy resins) (Composite recycling: Characterizing end of life wind turbine blade material, 2014) (Shokrieh et al., 2010).

The part fixing the blade to the hub, i.e. the root joint, is made of steel. It has holes for fixing screws. This part is covered from inside and outside with laminates to protect it against the action of corrosive agents. In new blade designs, root joints are rarely made of steel. Like other elements, they are made of composites. Fiberglass reinforced polymers constitute about two thirds of the entire mass of the wind turbine (Shokrieh et al., 2010) (Composite recycling: Characterizing end of life wind turbine blade material, 2014) (Xiaohui et al., 2013).

## WIND TURBINE BLADE EXISTENCE CYCLE

In the existence cycle of each technical object, including wind power plant blades, five basic stages can be named: expressing the need (NE), designing/constructing (C), manufacturing (M), exploitation (E) and post-consumer reuse/disposal (D). At each stage the object performs different tasks to meet the initially formulated goals (Legutko, 2007) (Thomson et al., 2015). Figure 4 shows a scheme of the wind power plant blade existence cycle.



Fig. 4. Phases of wind power plant blade existence cycle (own elaboration)

The first stage of blade existence cycle consists in expressing the need. It should be expressed in such a way that methods of its fulfilling are not suggested a priori. The next stage is blade constructing/designing. At this stage, requirements concerning blade strength, principle of operation and relations between structural elements are defined, and construction materials selected. As early as at this stage, selection of construction materials should take into account future post-consumer reuse of materials and

elements. The manufacturing stage, in turn, consists in production of wind power plant rotor blades with required features and the resultant utility potential predicted in the project. This stage includes actions oriented on designing technological processes and organisation of production processes, as well as material production of elements. The next stage, exploitation, is considered most important in the blade existence cycle. In that time, the blades perform functions for which they were designed and manufactured. The blade exploitation time is usually 20-25 years, during which they are subject to many exploitation processes, such as surface maintenance, and service and repairs resulting from harmful action of the environment on construction materials (especially in marine environment). In cases when large cracks are detected on blade surface, the blade is to be replaced by a new one (Composite recycling: Characterizing end of life wind turbine blade material, 2014).

The last, and simultaneously most problematic stage of wind power plant blade existence is disposal/post-consumer reuse. For some time, it was not mentioned as a separate phase in the existence cycle. The problem of post-consumer reuse should be taken into account at the stages of constructing, manufacturing and exploitation. From the point of view of rationalisation of material and energy use, the most appropriate approach is reuse of elements as a whole, or their processing. A number of possible ways of post-consumer reuse of wind turbine blades were worked out, including reuse of complete blades, recovery of materials and components, energy recovery, use of fragmented composite materials as fillers, and landfill storage (Composite recycling: Characterizing end of life wind turbine blade material, 2014). A systematised division of post-consumer reuse methods for materials composing wind power plant blades is given in Fig. 5.

The first form can be reuse of complete wind turbine blades, after their earlier regeneration. Solutions of this type were applied in many European countries with respect to relatively short blades. The regenerated blades were mounted in turbines with powers ranging from 10 kW to 1 MW, which radically decreased their cost.

## Possibilities for End Of Life wind turbine blades

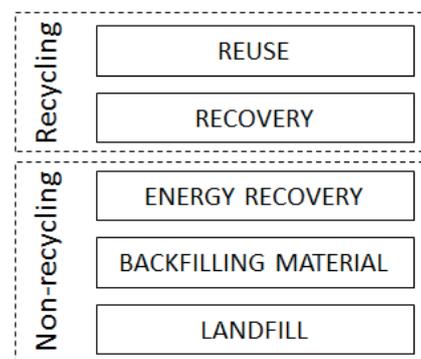


Fig. 5. Ways of post-consumer reuse of wind power plant blades (own elaboration)

Turbine regeneration procedures can include: visual and ultrasound diagnosis of blade condition, repainting, repair and balancing. They can also take into account recovery of materials and entire blade elements with their further reuse (without processing) in new blade constructions (Composite recycling: Characterizing end of life wind turbine blade material, 2014).

Another way of post-consumer reuse of materials coming from wind power plant blades can be recovery of energy contained in the structure of polymers. The energy recovery can take a form of combustion or co-combustion of polymers in high temperature, for instance in cement kilns (this solution was introduced by the German company Holcim). In this case, fragmented blades are introduced to the cement kiln and burnt. However, burning fiberglass in this way is difficult. The last method of post-consumer reuse is blade storage in a landfill. From the point of view of rational use of raw materials and post-consumer reuse of materials, this form is least profitable, as it does not make use of material and energy potentials contained in composites (Composite recycling: Characterizing end of life wind turbine blade material, 2014).

## METHODOLOGY OF EXAMINATION

The objects of examination were two wind turbine blades, of about 49 m in length each, made of material being a combination of polymers with carbon fibre and fiberglass, and laminated using the pre-preg type production process. The first examined blade had been a component of land-based wind power plant rotor, while the second one – of an offshore wind power plant (producers' data).

The examination was performed using the LCA method and the software SimaPro 7.1. The LCA method makes it possible to assess the impact of the technical object existence cycle on the environment. The analysis covers the entire life cycle, taking into account its consecutive stages. The assessment is based on the information concerning the amounts and types of materials used at each existence cycle stage and the data concerning energy consumption. Environmental impacts and harmful actions have the form of numbers, which makes it possible to identify dominating life cycle areas. This model can be used by a producer for structural modernisation or improvement of the product. It can also be helpful for designers who have to choose an individual construction solution (Piasecka et al., 2015). Figure 6 shows possibilities of use of the LCA methodology to assess the environmental impact of wind power plant blade life cycle.

The LCA method-based assessment was done in accordance with the standard ISO 14000 and consisted of four consecutive basic steps: expressing goal and range, analysing the set of inputs and outputs (LCI), assessing the impact (LCIA), and interpretation.

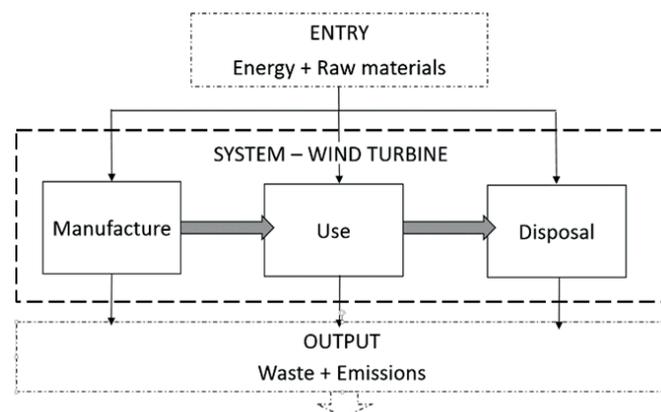


Fig. 6. Scheme of relations with environment, taking into account flow of raw materials and elements composing the wind turbine blade system in LCA method (own elaboration)

The LCIA phase made use of Ekowskażnik 99 modelling. The analysis was iterative by nature and was characterised by numerous feedbacks. After each analytical step, current interpretation of the obtained pieces of information was performed. In the paper, the comparison analysis of two objects is presented, which were the land-based wind power plant blade and the offshore wind power plant blade. The basic goal of the analysis was describing the existing reality (retrospective LCA), but it also included modelling of future changes and formulating recommendations for working out more pro-environmental solutions (prospective LCA). The applied procedure has the character of classical LCA process examination. The starting point for the analysis was the thesis that blades of land-based wind power plants generate smaller negative impact on the environment than those of offshore wind power plants (which have to be more robust and resistant to the action of aggressive marine environment).

The majority of processes executed within the analysed blade life cycle stages (constructing, manufacturing, exploitation, and post-consumer reuse) take place in Europe. Since the performed LCA analysis in comparative by nature, the systems of analysed products were arranged in a comparable manner with respect to the depth and width of the analysis, as well as the data quality. The basic assumption of the analysis is presenting differences in the scale of impact on the environment, which mainly result from changes in production and materials used for blades. The geographical range and time interval of the data are the same, while the technological ranges are different. The geographical range is European-wide, which results from the fact that companies being data providers have very strong position on the entire European market. Part of data, especially those concerning the place of manufacturing, had specific, local nature related to a given source. On the other hand, taking into account European-wide sales range, the exploitation and post-consumer reuse can be executed on the entire European territory and the data and recommendations concerning these blade life cycle stages are continent-wide. The time interval covers the same 25 years of exploitation. From the

spatial point of view, no significant effects are observed, therefore the same place of manufacturing is assumed, but different technologies which lead to manufacturing of blades with different parameters for land-based and offshore applications.

All limitations and exclusions were done simultaneously for all product systems. The analysis neglected stages of blade storage, sales and distribution of both examined blades. As a result, product systems were uniformly loaded with the same simplifications, which introduced a similar level of uncertainty. The exclusion criterion was below 0,01% of participation, both at the level of entire life cycle, and contribution to environmental impact at the level of a given stage of life cycle of both examined blades. The performed analysis can be qualified as *bottom-up* type analysis. The planned analysis advancement level places it among detailed analyses. The term “manufacturing” is understood in the paper as all processes related with blade production, its individual materials and components and, wherever possible, processes reaching the elementary streams (raw material mining and final emission to the environment). The LCI results for stages of manufacturing, exploitation, and post-consumer reuse will be the object of complete LCA assessment, including the assessment of LCIA impact. The data used in the analysis were obtained from blade producers or taken from programme SimaPro 7.1 databases.

## RESULTS AND THEIR ANALYSIS

The paper presents solely the results obtained for the grouping and weighting phases. A characteristic feature of the used method Ekowskażnik 99 is possibility to present the obtained results as environmental points (Pt). A thousand of environmental points corresponds to the impact of one European on the environment during one year. The object of analysis was the range of negative environmental after-effects generated during one life cycle, or during its individual stages, for one land-based wind turbine blade and one offshore wind turbine blade, taking into account three impact areas, eleven impact categories, and three emission areas.

The life cycle of the offshore wind power plant blade has higher level of negative impact on the environment. The total number of environmental points is equal to 3688 Pt for post-consumer reuse in the form of landfill storage, and 1258 Pt for recycling. For both blade types, the life cycle taking into account recycling processes generates a smaller number of negative environmental after-effects (Fig. 7).

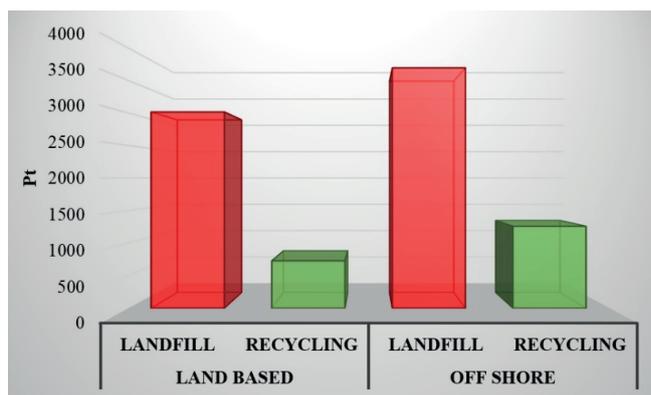


Fig. 7. Results of grouping and weighting of environmental after-effects in one material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

Larger number of negative environmental after-effects in the existence cycle of offshore wind power plant blade is mainly caused by higher level of harmful substance emissions at the manufacturing stage, which amounted to 2669 Pt. In the remaining existence cycle stages of both blade types, no significant differences in total level of environmental impact were observed (Fig. 8).

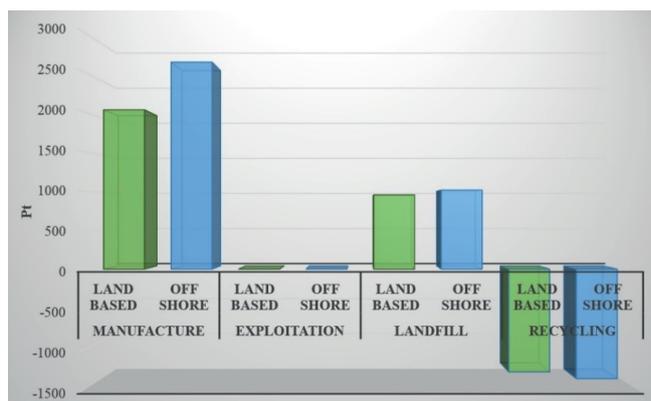


Fig. 8. Results of grouping and weighting of environmental after-effects in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

The list of substances and processes causing the largest number of negative environmental after-effects in consecutive stages of material existence cycle of land-based and offshore wind power plant blades includes emission of cadmium ions, nitrogen oxide, sulphur dioxide, arsenic, dinitrogen oxide, cuprum ions, and particles of up to 10 µm in size (Table 1).

Tab. 1. Results of grouping and weighting of substances and processes causing the largest number of negative environmental after-effects in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

Substance	Compartment	Manufacture		Exploitation		Landfill		Recycling	
		Land-based	Off shore	Land-based	Off shore	Land-based	Off shore	Land-based	Off shore
Cadmium, ion	Water	2,236	2,814	0,000	0,000	869,570	925,761	0,173	0,190

Substance	Compartment	Manufacture		Exploitation		Landfill		Recycling	
		Land-based	Off shore	Land-based	Off shore	Land-based	Off shore	Land-based	Off shore
Gas, natural, in ground	Raw	680,518	725,142	0,003	0,003	0,680	0,720	0,000	0,000
Oil, crude, in ground	Raw	474,997	506,145	0,002	0,002	5,480	5,807	0,000	0,000
Nitrogen oxides	Air	128,227	143,172	0,000	0,001	1,592	1,686	-86,649	-92,205
Carbon dioxide, fossil	Air	112,879	120,281	0,000	0,000	0,991	1,052	0,000	0,000
Sulphur dioxide	Air	104,057	105,935	0,000	0,000	0,200	0,211	0,000	0,000
Cadmium	Air	98,680	106,113	0,000	0,000	0,030	0,031	0,236	0,264
Particulates, < 2.5 µm	Air	76,632	81,657	0,000	0,000	1,012	1,071	0,000	0,000
Arsenic	Air	53,632	57,323	0,000	0,000	0,004	0,004	0,000	0,000
Particulates, > 2.5 µm, and < 10µm	Air	50,325	53,625	0,000	0,000	0,135	0,143	0,000	0,000
Dinitrogen monoxide	Air	45,204	48,299	0,000	0,000	0,012	0,012	0,115	0,123
Arsenic, ion	Water	25,649	33,426	0,000	0,000	19,173	20,388	8,782	9,546
Copper, ion	Water	0,648	0,806	0,000	0,000	28,822	30,180	0,127	0,139
Nickel	Air	16,271	32,583	0,000	0,000	0,017	0,018	4,318	4,629
Methane, fossil	Air	8,245	8,785	0,000	0,000	1,791	1,904	0,000	0,000

The majority of negative after-effects generated in the manufacturing stage of both land-based and offshore wind power plant blades leads to deterioration of human health, decrease of environmental quality, and depletion of fossil resources. Storage of blades which cannot be further exploited poses a significant threat to health (land-based blade: 896 Pt, offshore blade: 954 Pt). Post-consumer reuse of plastics, and other materials and elements of blades of both types in the form of recycling would make it possible to reduce significantly negative impacts concerning depletion of fossil resources (land-based blade: -1256 Pt, offshore blade: -1338 Pt) (Fig. 9).

In the cases of compounds leading to deterioration of human health, the highest level of harmful emissions at the manufacturing stage for both blade types is recorded for inorganic substances causing respiratory diseases (land-based blade: 370 Pt, offshore blade: 697 Pt). During landfill storage of blades, in turn, many harmful carcinogens may penetrate to the environment (land-based blade: 889 Pt, offshore blade: 946 Pt) (Fig. 10).

Quality decrease of natural environment is mainly caused by emissions of ecotoxic substances, the largest amounts of which are created at the manufacturing stage (land-based blade: 64 Pt, offshore blade: 91 Pt) and the landfill storage stage (land-based blade: 54 Pt, offshore blade: 57 Pt) (Fig. 11).



Fig. 9. Results of grouping and weighting of environmental after-effects for three areas of impact, in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

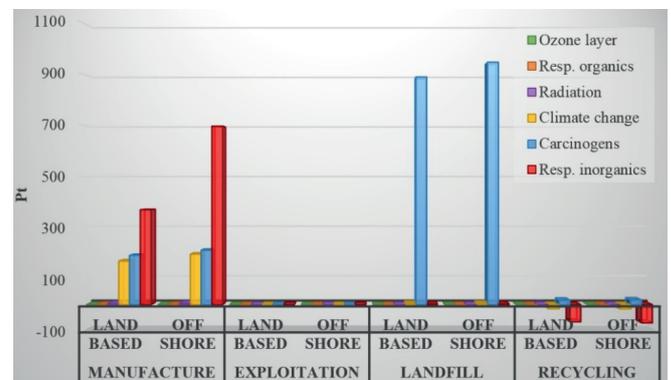


Fig. 10. Results of grouping and weighting of emissions leading to deterioration of human health, in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

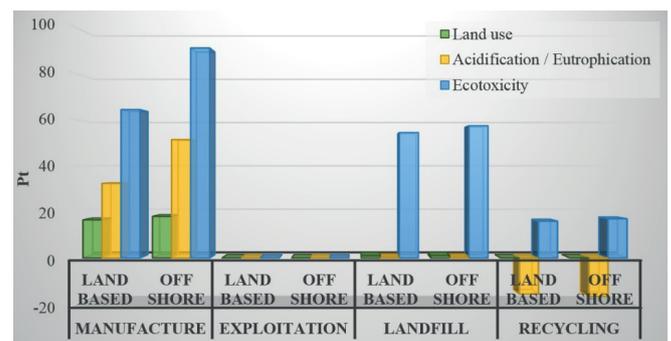


Fig. 11. Results of grouping and weighting of processes and emissions leading to the decrease of environmental quality, in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

As far as processes affecting depletion of fossil resources are concerned, the highest level of negative environmental after-effects is recorded for the category of processes related with mining of fossil fuels (mainly crude oil), at the manufacturing stage (land-based blade: 1178 Pt, offshore blade: 1321 Pt). The post-consumer reuse in the form of recycling would limit

the harmful impact in the analysed range by 1256 Pt for land-based blade and by 1337 Pt for offshore blade (Fig. 12).



Fig. 12. Results of grouping and weighting of processes leading to depletion of fossil resources, in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

Taking into account three main areas of emissions of compounds having negative environmental effect, the highest level of harmful impacts for the land-based wind power plant blade life cycle was recorded in the case of emission to water environment, while for the offshore blade life cycle – in the case of emission to the atmospheric environment. The post-consumer reuse of plastics, and other materials and elements of both blade types in the form of recycling would limit radically the emission of harmful substances to the water environment (by about 75-80%) (Fig. 13).

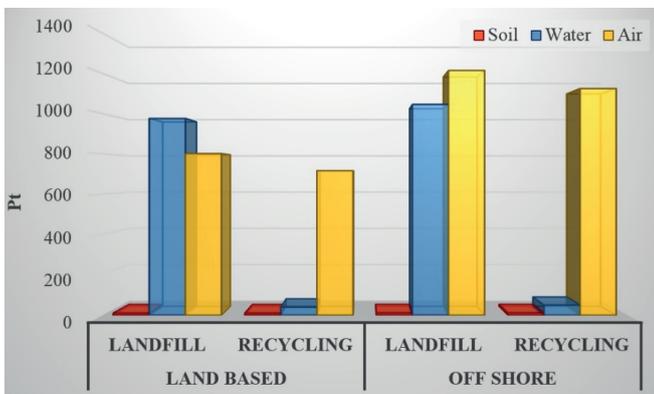


Fig. 13. Results of grouping and weighting for three areas of emission, in material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

The highest level of emissions of harmful substances to the atmosphere was recorded at the manufacturing stage (land-based blade: 793 Pt, offshore blade: 1204 Pt), while to the water environment – at the landfill storage stage (land-based blade: 943 Pt, offshore blade: 1003 Pt) (Fig. 14).

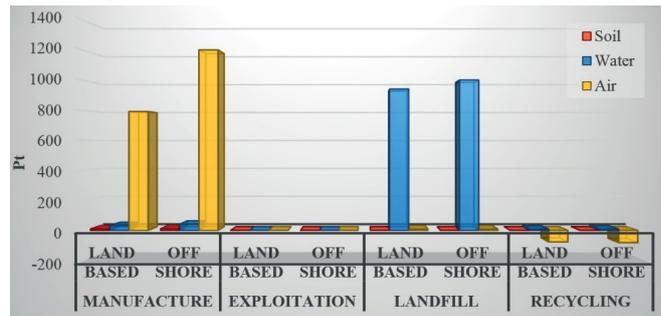


Fig. 14. Results of grouping and weighting for three areas of emission, in consecutive stages of material existence cycle of wind power plant blades, taking into account possibility of their post-consumer reuse [own research]

## SUMMARY AND CONCLUSIONS

Year by year, growing interest is being observed in renewable energy sources, including wind energy (of both land-based and offshore type). Each power plant affects somehow the environment, but not to the same extent. The element of a wind power plant which has a key impact on the plant's power output, but also causes most problems with post-consumer reuse, are rotor blades. In the modern world, growing attention is paid to eco-designing which aims at reducing negative environmental impact of a given object during its entire life cycle – from construction, through exploitation, until post-consumer reuse. A tool for environment friendly designing is *Life Cycle Assessment* (LCA).

The main goal of the paper was achieved through performing a comparison analysis of material existence cycle stages for land-based and offshore wind power plant blades.

Higher level of harmful impacts on the environment was recorded for the life cycle of offshore wind power plant blade. For both blade types, the life cycle taking into account recycling processes had smaller negative environmental impact. The greatest number of negative environmental after-effects in the existence cycles of both blade types was mainly caused by very high level of emissions of harmful substances at the manufacturing stage. The list of substances which have the highest harmful impact on the environment in the wind power plant blade existence cycle includes, among others, cadmium, nitrogen oxide, carbon dioxide, sulphur dioxide, arsenic, dinitrogen oxide, cuprum, and particles of up to 10 µm in size.

The manufacturing stage is a source of the majority of negative impacts in each of the analysed impact areas. In the case of substances leading to the deterioration of human health, the highest level of harmful emissions was recorded for inorganic substances causing respiratory diseases. The decrease of environmental quality, in turn, was mostly affected by emissions of ecotoxic substances. Within the range of processes leading to depletion of fossil resources, the highest level of negative environmental after-effects was

recorded for the category of processes related with mining of fossil fuels (mainly crude oil).

For the life cycle of land-based wind power plant blade, the highest level of harmful impact was recorded in the case of emission to the water environment, while for offshore blade – to the atmospheric environment. Most of harmful substances are emitted to the atmosphere at the manufacturing stage, while to the water environment - at the landfill storage stage.

Based on the performed research, it is postulated to:

- reduce the negative environmental impact of the manufacturing process, being the existence cycle stage of highest negative impact to human health, environmental quality, and depletion of fossil resources, through introducing modern technologies with lower energy and material consumption, and lower emission of harmful substances;
- create the best possible pro-environmental algorithm of management for plastics, and other materials and elements of wind power plant blades after the end of their exploitation, taking into account in particular recycling processes;
- work upon more pro-environmental construction materials, which will simultaneously preserve relevant technical, mechanical and quality parameters needed for playing certain roles in wind power plant elements;
- design a structure which would enable simpler segregation of individual materials and their easier identification for post-consumer reuse,
- work out comprehensive, pro-environmental standards concerning methods of post-consumer reuse of plastics, and other materials and elements of wind power plant blades.

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