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Life Cycle Analysis of Ecological Impacts of an Offshore and a Land-Based Wind Power Plant

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Abstract: This study deals with the problems connected with the benefits and costs of an offshore wind power plant in terms of ecology. Development prospects of offshore and land-based wind energy production are described. Selected aspects involved in the design, construction, and operation of offshore wind power plant construction and operation are presented. The aim of this study was to analyze and compare the environmental impact of offshore and land-based wind power plants. Life cycle assessment analysis of 2-MW offshore and land wind power plants was made with the use of Eco-indicator 99 modeling. The results were compared in four areas of impact in order to obtain values of indexes for nonergonomic (impact on/by operator), nonfunctional (of/on the product), nonecological (on/by living objects), and nonsozological impacts (on/by manmade objects), reflecting the extent of threat to human health, the environment, and natural resources. The processes involved in extraction of fossil fuels were found to produce harmful emissions which in turn lead to respiratory system diseases being, thus, extremely dangerous for the natural environment. For all the studied areas, the impact on the environment was found to be higher for land-based wind power plants than for an offshore wind farm.

Keywords: offshore wind energy production; renewable energy sources; environmental impact; life cycle assessment

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1. Introduction

Recent years have witnessed a significant growth in offshore wind energy production. As compared to other renewable energy sources, it has been developing most rapidly. In Europe, the power accumulated in offshore power plants is now 12.6 GW. In 2016, wind energy production was the target of many energy production industry investors. In Europe, the amount of 27.6 mld. € has been spent on this kind of investments including 18.2 mld. € for offshore wind farms. The number of land investments has dropped by 5% (down to 9.4 mld. €), which is the first drop reported during the last few years. It is expected that by 2030, 7–11% of electric energy in the EU will be produced in offshore wind power plants. It is estimated that by the year 2030, the cumulative capacity installed in European offshore energy power plants will range from 65 to 85 GW [1–4].

The technical resources available to investors for development of offshore wind energy production in Europe is impressive. An analysis of areas to be used for this kind of investment (with the exception of, for example protected areas such as NATURA 2000—protection area of natural habitats and species specific types within the territory of the European Union, areas used for fishing and sailing or strategic ones) shows that most of them are characterized by a high coefficient of electric energy production (above 10,000 TWh/year/100 km^2) [2,5,6].

A typical wind farm consists of nearly 8000 different elements, whereas, the most important ones are: rotor with blades, gondola, tower and a foundation. Figure 1 shows the technological environment of an offshore wind farm with the most commonly used types of foundations. Monopile is the most popular type of foundation (74% of European offshore installations) due to the low construction costs, simplicity, and the possibility of being used in shallow water (less than 20 m deep). The post is drilled or pounded into the sea bottom. In the beginning, a GBS (gravity-based structure) was used in shallow water (up to 15 m deep); currently it is being adjusted to bigger and bigger depths (nearly 30 m). A large area and the weight of the foundation protect the power plant from the forces of waves and wind. The foundation of bases of the tripod and triple type are fixed on three posts so that they can be used in deeper water. Three ends of the base are set or pounded into the sea bottom to support the central axis of the installation, connecting the axis with a turbine. Whereas the foundation of jacket type consists of a larger structure made of steel bars which are symmetrically sited beyond the main axis of the entire structure (efficiency of materials) [2,7,8].

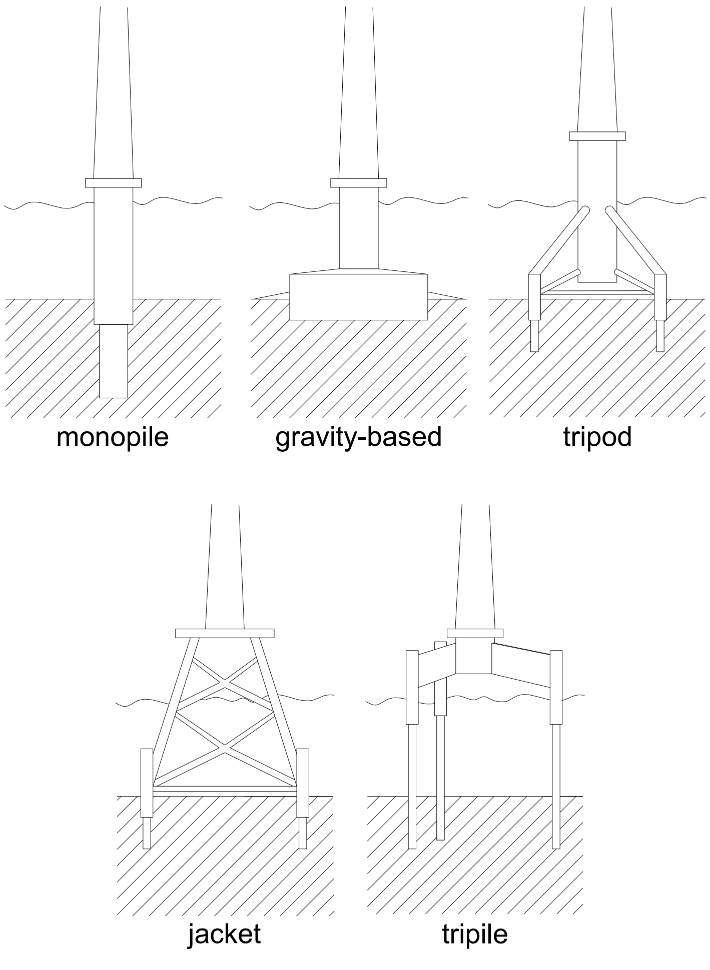

Figure 1. Technological environment and methods used for offshore wind farm anchoring. Authors' own work.

The major differences between construction of a land and an offshore wind farm are caused by the impact of two factors: the sea environment and high installation costs. Nowadays, investment costs involved in construction of an offshore power plant can be even two times higher than for the land power plant. Offshore turbines must be more resistant to corrosion, easy to maintain, and have high storm resistance. Therefore, materials, specialist coat systems, and compartments with filtered and ventilated air need to be used for protection against the effect of salty mist. The anchoring system and the structure of the tower need to take into consideration such factors as: tides and currents, height and power of waves, ships, icebergs, increased turbulences, and wind power during storms. The design of an offshore wind farm needs to take into account the environmental and ecological aspects—particularly it needs to focus on avoiding disruption of the water ecosystem in the location site. They cannot be situated within the flyways of birds. They are to be provided with additional protective devices in order to avoid influence of uncontrolled oil leaks from mechanical components (e.g., during failure of the propulsion transmission system or a transformer). The foundation of an onshore turbine consists of plate foundations made of reinforced concrete. The foundation is concreted in situ. After excavation, the hole is filled with approximately 475 m^3 of concrete with approximately 36 tons of steel reinforcement. The offshore turbines are placed at the depth of 6.5–13.5 m, calculated from sea surface to sea bed, for average water level. The foundation consists of a foundation pile, a transition piece, a boat landing platform, a platform, and cathode protection. As the dimensions for the foundation pile may fluctuate due to various sea depths, different assumptions are made for the foundation dimensions, for example: foundation pile made of high-strength steel—length: 29.7 mm, diameter: 4.0 mm, thickness: 30 mm, 45 mm, 50 mm; dimensions for the transition piece—length: 17.0 mm, diameter: 4.24 mm (bottom), 4.0 mm (top), thickness: 40 mm and 50 mm [9–14].

Considering the above, the aim of the study is an analysis of the environmental impact of an offshore wind power plant life cycle in comparison with a land wind power plant.

The research problem was formulated as a question: how does the life cycle of an offshore wind farm affect the environment in the four areas of impact: nonergonomic, nonfunctional, nonecological, and nonsozological, reflecting the extent of threat to human health, the natural environment, and exhaustion of natural resources?

To resolve the problem, an original methodology has been developed to investigate the environmental impact of two wind turbines, using the life cycle assessment (LCA) method.

2. Materials and Methods

2.1. The Concept of Wind Farm Harmfulness

The environmental impact of a wind farm involves its influence on the operators, products, and natural and manmade objects of the environment. It appears in the form of different factors, e.g., informative, energetic or material ones. The degree of the impact is different and depends on the abovementioned factors. They yield different effects, depending on sensitivity of the environment particular elements to the impact of these factors. Therefore, it is impossible to express the impact of a wind power plant by only one characteristic. The environmental impact is a synthetic, complex and overall characteristic which is made up of component characteristics, including harmful relations between the wind power plant and particular elements of the environment [15,16].

Energy effectiveness e_{en}, economic effectiveness e_{eko} and ecological one e_{EKO} depend on unit profits ($K_{en,eko,EKO}$) and expenditures ($N_{en,eko,EKO}$), environmental impact ($D_{s\text{-}o\text{-}c}$) and operation time (t_e):

$$SP(e_{en,eko\ EKO})_{zEW} = f(K_{en,eko,EKO}, N_{en,eko,EKO}, D_{s\text{-}o\text{-}c}, t_e)_{zEW} \tag{1}$$

In this case, profits ($K_{en,eko,EKO}$) and expenditures ($N_{en,eko,EKO}$) depend on the negative influence of the system ($D_{s\text{-}o\text{-}c}$), nonergonomic (D_o), nonfunctional (D_f), nonecological (D_{Eko}), nonsozological (D_s) impact and operation time (t_e) and are described as follows:

$$(K_{en,eko,EKO}, N_{en,eko,EKO})_{zEW} = f\ (D_{s\text{-}o\text{-}c}, D_o, D_f, D_{Eko}, D_s, t_e) \tag{2}$$

where:

$SP(e_{en,eko,EKO})_{zEW}$—goals, postulated states: energy, economic, and ecological effectiveness of operation of a wind power plant—all working units,

$e_{en,eko,EKO}$—energy, economic, and ecological effectiveness of wind power plant unit operating in the natural environment,

$K_{en,eko,EKO}$—energy, economic, and ecological profits from wind power plant unit operating in the natural environment,

$N_{en,eko,EKO}$—energy, economic, and ecological expenditures of wind power plant unit operating in the natural environment,

$D_{s\text{-}o\text{-}c}$—negative influence of a system, environment, and man,

D_o—nonergonomic (impact on/by operator) of technical system operators and the environment,

D_f—nonfunctional (of/on the product) of technical system's processing variables,

D_{Eko}—nonecological (on/by living objects) *of living environmental objects*,

D_s—nonsozological (on/by manmade objects) of artificial objects of system and/or environment,

t_e—operation time [17].

The degree of impact of a wind farm system–environment–human, causing reduction of benefits and increase in ecological costs can be evaluated on the basis of threats posed by harmful emissions and assessment of detrimental effects they lead to. According to dependence (2), it can be written:

$$(K_{EKO}, N_{EKO})_{zEW} = f\ (D_{s\text{-}o\text{-}c}, D_o, D_f, D_{Eko}, D_s, t_e) \quad (3)$$

By analogy to efficiency, from the point of view of the operators' ergonomics, the wind farm functionality, living creatures, and the impact of ecological benefits and costs (D) of an offshore wind power plant operation, a ratio of losses (S) to costs (N) [17] can also be formally defined:

$$D = S/N \quad (4)$$

The stream of losses (S), reflects a given informative–energy–material resource and it can particularly include "social danger", harmful information (audio, visual, smell, etc.),—expressed by the number of occurrences or the value of liquidation costs and losses (energy, vibrations, noise, hum, heat light, blast, impetus, etc.)—referred to by an adequate unit of (time, cycle, rhythm, period, volume surface, etc.) and an amount of substance emitted in a time unit (gaseous, liquid, solid) with different impact degree (sulfur, chlorine, heavy metals, oxygen compounds, etc.) (Figure 2). This provides the possibility to define detailed measures of danger. Direct expenditures N include, for example, acquisition of resources and energy as well as the process-related costs NP including: energy supply, technological costs, machine operation and maintenance costs, manufacturing and intellectual outlays, as well as costs of the resources processing NU, NS such as: resources processing, components and machine related processes, utilization costs ND involved in: logistics, preparatory processes, recycling of materials, energy and resources; costs connected with reduction of the impact on the environment NO, including: minimization of the costs of emission, pollution and the destructive impact on the environment. Examples of a useful (functional) effect U of a wind farm operation include: benefits from wind farm productiveness, the major effect UG being: minimization of emission related to conventional energy production methods, additional effect UD: social advantages. In turn, the following unrecovered losses S can be distinguished: degradation of the environment caused by exploitation of natural resources, functional losses S': reduction of the nominal power of conventional power plants; the process related losses S'' including operating costs: power supply, monitoring, operation, and maintenance [11,16].

Nonergonomics is a characteristic used to express the degree of a wind farm effect on/by its operator. Nonfunctionality stands for the negative impact of/on the product or losses to be generated while its functioning. Nonfunctionality involves mainly faulty operation, inefficiency, and the output disturbance as well as deviations from the nominal operating conditions in reference to the environment, the object, and the system. The term nonecological means characteristics of a harmful, though unintended, influence related to the wind farm operation on/by living objects of the environment. Actions aimed at reduction of environmental unfriendliness should be, however, supported by minimizing the impact, as failing to do so can cause an increase in the remaining environmental effects and less improve the wind power plant's general impact [18]. Impact of the environment's living and artificial objects referred to energy or material related factors is caused by their vitality, excessive concentration and volume which diverge from the natural state. It causes disruption of natural biological processes which eventually leads to devastation. In relation to wind power plants, nonsozological means the harmful impact of a rotor on/by manmade objects of the environment; that is, everything that has been created by people from processed or natural resources to be intensively used [16,17,19].

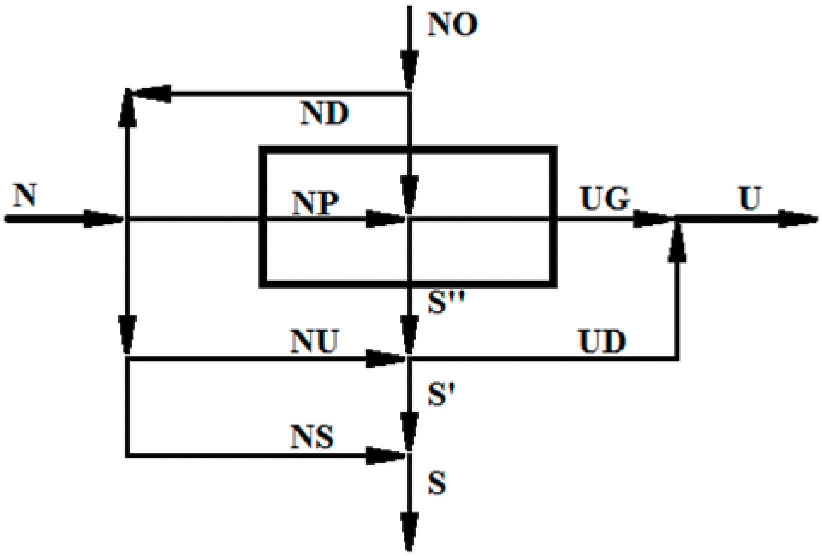

Figure 2. Model of an operation system: *N* direct outlays, *NP* process-related outlays, *NU*, *NS* processing related outlays, *ND* utilization outlays, *NO* protection outlays; effects: *U* functional, *UG* general, *UD* additional; losses: *S* unrecovered, *S′* useful, *S″* process related. Authors' own study.

2.2. Models for Analysis and Assessment of Ecological Impact and Benefits

A life cycle of a wind farm is accepted to consist of four successive stages (Figure 1 in Reference [16]): formulation of the necessity to design, construct, manufacture, use, and finally, after the end of its operation, to recycle it. The last stage of each life cycle is also a contribution to the new one. Assessment of the offshore and land wind farm life cycles contributes to formulation of directives and recommendations to be used for creation of more ecological technical objects in the form of newly formulated needs to be implemented in successive stages of the wind power plant existence [8,20,21].

The study presents an analysis of several single components combined in one system—wind farm—according to the life cycle assessment (LCA) model. The LCA rating method, in accordance with ISO 14000, consists of four successive basic elements: definition of the objective and scope, analysis of a set of inputs and outputs (LCI), impact assessment (LCIA), and the interpretation. The entire evaluation is an iterative process, distinguishing multiple feedback loops. Each and every analytical phase was followed by operational interpretation of the obtained data. Eco-indicator 99 belongs to the group of methods for modeling the environmental impact of an environmental endpoint mechanism. The process of characterization is done for the eleven impact categories, coming in three larger groups referred to as impact areas or categories of damage. There are the following areas of impact: human health, ecosystem quality, and resources. The results of the impact area indicators are further analyzed through normalization, grouping, and weighing into the final Ecolabel [22,23].

The aim of this analysis is a numerical determination of the impact on the environment of a life cycle of 2 MW offshore (monopile foundation) and land-based wind farms. The choice of such an installed capacity value was dictated by local conditions in Central and Eastern Europe, where 2 MW facilities are currently the most commonly used. The analysis aims at a description of the current situation (LCA retrospective), but also future changes in modeling and formulation of recommendations to be used for development of more ecological solutions (LCA prospective). The procedure involves classical, process-based LCA research, whose tasks include quantitative determination of the analyzed object life cycle impact on the benefits and outlays. Directives and recommendations included in the group of ISO 14014 norms are used as the key point reference. Four stages of LCA were included: formulation of the goal and scope, analysis of the set of entrances and exits, assessment of the life cycle impact, and interpretation.

The area of Poland was accepted as the geographical border, and the time scope was 25 years (estimated time of a wind power plant operation) [24–27]. Production of electric energy was accepted to be the wind power function. Whereas, the amount of electric energy produced by the considered system during a year was defined as a functional unit. Stages of transport, sale, technical tests, and storage were not analyzed. The main reason was not enough data and big differences in the transport process impact, depending on the wind power plant location site.

An analysis of the life cycle impact assessment (LCIA) was made with the use of a computing program SimaPro. Eco-indicator 99 was based on end points of the environmental mechanism. Due to a lack of clear reasons for exclusions, all categories of the impact included in Eco-indicator 99 were analyzed. The level of the impact exerted by selected processes of the wind farm post use utilization was analyzed as well (25% storage on landfills and 75% recycling [14,16,28,29]; the possibility of combustion with energy recovery was neglected due to the structure of high content of inflammable materials). Dominant areas affecting human health, the quality of the environment, and depletion of natural resources were identified. The cut of level was 0.1% [30].

In order to calculate the numerical value of the wind power plant impact on the operators' health, DALY (disability adjusted life years) unit was used. Assessment of the impact on the environment was performed with the use of a scale from 0 to 1, where 0 stands for a lack of impact on the human health and 1 stands for death. The impact that causes a change in the ecosystem quality was treated as a separate category of impacts. The number of species which disappear in a given area during a year due to the adverse effect of such factors as: acidification/eutrophication, land management, ecotoxicity or climate change (unit: PAF·m^2/a and PDF·m^2/a) was accepted to be the measure. Impacts connected with depletion of natural resources is divided into two categories: extraction of fossil fuels and minerals. These categories are assessed in terms of increasing costs connected with extraction of resources and expressed in MJ surplus energy unit [23,31–33].

At the characterization stage, the results are presented in four units: DALY is the number of years spent in the disease or lost at all, PDF·m^2/a—potentially lost part of plant species, PAF·m^2/a—a potentially damaged part of these species, and MJ surplus energy—additional energy needed for future use of substitutes, inferior quality, sources of material or energy supply. In turn, environmental points (Pt) are units provided by normalization, and next, grouping and weighing the results obtained at the stage of characterization. A thousand environmental points are equal to a negative impact on the environment of one European during a year [31–33].

3. Results and Their Analysis

The study presents results from the stage of characterization, grouping, and weighing obtained with the use of modeling by Eco-indicator 99. An analysis of negative environmental effects generated during one life cycle of the land and offshore wind farm was performed including four kinds of impacts, eleven impact categories, and three impact areas.

The first stage of analysis within LCIA (impact assessment) was characterization. All three categories (operators' health—unit: DALY; the environment quality—units: PAF·m^2/a and PDF·m^2/a; materials—unit: MJ surplus energy) and other eight (out of eleven) impact categories make up the nonergonomic impact. The highest level of negative impacts, both for the land-based and offshore power plant, was reported for, respectively: human health—emission of inorganic compounds—cause of respiratory system diseases (0.999 DALY—land-based wind farm, 0.954 DALY—offshore wind farm), for deterioration of the environment quality—emissions of ecotoxic compounds

(879,423.9 PAF·m^2/a—land wind farm, 1,320,083.6 PAF·m^2/a—offshore wind farm) and for exhaustion of natural resources—processes connected with extraction of fossil fuels—(2,437,145.9 MJ—land wind farm, 1,752,643.1—offshore wind farm). In terms of nonergonomic impacts, it is the land-based wind power plant that produces a higher level of adverse effects on the human health and exhaustion of natural resources, whereas, in terms of the environment deterioration, this is the offshore wind power plant (Table 1).

Table 1. Results of characterization of the environmental effects that occur in life cycles of land-based and offshore wind farms. Authors' own research.

Types of Impact	Impact Category	Land Based	Offshore	Unit
NONERGONOMICAL	Resp. organics	0.002	0.002	DALY
	Resp. inorganics	0.999	0.954	DALY
	Radiation	0.010	0.011	DALY
	Carcinogens	0.215	0.284	DALY
	Ecotoxicity	879,423.900	1,320,083.600	PAF·m^2/a
	Land use	10,910.827	7562.715	PDF·m^2/a
	Minerals	512,922.390	504,011.090	MJ surplus
	Fossil fuels	2,437,145.900	1,752,643.100	MJ surplus
NONFUNCTIONALITY	Radiation	0.010	0.011	DALY
	Land use	10,910.827	7562.715	PDF·m^2/a
	Minerals	512,922.390	504,011.090	MJ surplus
	Fossil fuels	2,437,145.900	1,752,643.100	MJ surplus
NONECOLOGICAL	Radiation	0.010	0.011	DALY
	Climate change	0.351	0.379	DALY
	Ozone layer	0.001	0.001	DALY
	Ecotoxicity	879,423.900	1,320,083.600	PAF·m^2/a
	Acidification/Eutrophication	29,954.917	25,882.851	PDF·m^2/a
	Land use	10,910.827	7562.715	PDF·m^2/a
	Minerals	512,922.390	504,011.090	MJ surplus
	Fossil fuels	2,437,145.900	1,752,643.100	MJ surplus
NONSOZOLOGICAL	Radiation	0.010	0.011	DALY
	Land use	10,910,827	7562.715	PDF·m^2/a
	Minerals	512,922.390	504,011.090	MJ surplus
	Fossil fuels	2,437,145.900	1,752,643.100	MJ surplus

DALY—the number of years spent in the disease or lost at all, PDF·m^2/a—potentially lost part of plant species, PAF·m^2/a—a potentially damaged part of these species, MJ surplus energy—additional energy needed for future use of substitutes, inferior quality, sources of material or energy supply.

Nonfunctionality impact is described with the use of four impact categories: emission of radioactive elements (human health—DALY unit), use of land (quality of the environment—PDF·m^2/a unit), and processes connected with extraction of minerals and fossil fuels (sources—MJ unit, surplus energy). The last of the listed categories is characterized by the highest negative impact in the considered type of impact (2,437,145.9 MJ—land wind power plant 1,752,643.1—offshore wind power plant). In respect of nonfunctionality impact, higher levels of adverse impact on the environment and depletion of resources was found for a land-based wind farm, whereas an offshore wind power plant was found to pose more threat to human health (Table 1).

Nonecological impact is the sum of negative impacts of eight impact categories from three areas: operators' health (emission of radioactive elements causing climate changes and ozone layer depletion), the environment quality (emission of ecotoxic substances causing acidification or eutrophication and processes connected with land use), and resources (processes connected with extraction of minerals and fossil fuels). The highest impact on the health of humans and animals of both considered wind farms was found for emission of substances causing climate changes (0.351 DALY—land-based wind farm, 0.379 DALY—offshore wind farm). Emissions of ecotoxic substances (879,423.9 PAF·m^2/a—land-based wind farm, 1,320,083.6 PAF·m^2/a—offshore wind farm) were found to be the most harmful to the environment. In turn, fossil fuel extraction processes (2,437,145.9 MJ—land wind farm, 1,752,643.1—offshore wind farm) contributed to exhaustion of natural resources to the highest extent. In terms of nonecological impact, it w the offshore wind power plant that is characterized by higher levels of adverse effects on human health and the environment, whereas a land-based wind power plant is more harmful in respect to natural resource depletion (Table 1).

Nonsozological impact is referred to as a summary negative impact on benefits and environmental costs for four categories: emission of radioactive elements, processes connected with land use, processes of minerals, and fossil fuel extraction. In this type of impact, it is the excessive exploitation of fossil fuels that causes the most negative impact (2,437,145.9 MJ—land-based wind power plant, 1,752,643.1—offshore wind power plant). In this impact area, it is the land-based wind power plant which poses a bigger threat to the environment and natural resources depletion, whereas an offshore wind power plant is more harmful to the human health (Table 1).

The second stage of LCA analysis was normalization of the characterization results and their grouping and weighing, according to the earlier accepted assumptions (particularly European environmental conditions). Among eight categories of the nonergonomic impact, the highest level of negative effects was found for the processes connected with fossil fuel extraction (58,004 Pt—land-based wind farm, 41,713 Pt—offshore wind farm) and for emission of inorganic compounds causing respiratory system diseases (31,528 Pt—land-based wind farm, 24,846 Pt—offshore wind farm). An offshore wind farm had a bigger impact on the environment as compared to a land-based wind farm, for exactly half of the analyzed categories that make up the nonergonomic impacts (emission of organic substances causing respiratory system diseases, radioactive, carcinogenic, and ecotoxic elements) (Figure 3).

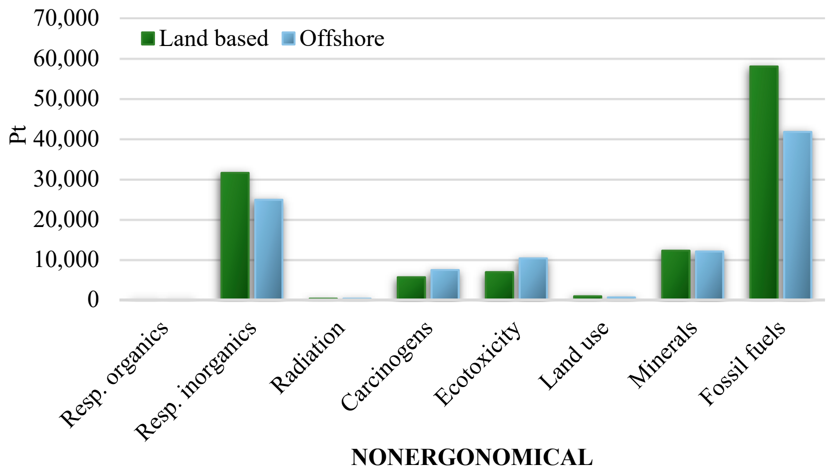

Figure 3. Results of grouping and weighing environmental impacts for ergonomic impacts involved in life cycles of land based and offshore wind farms. Authors' own research.

An analysis of four impact categories that make up the nonfunctionality impacts shows that two of them, that is, fossil fuels extraction processes (58,004 Pt—land-based wind farm, 41,713 Pt—offshore wind power plant) and minerals (12,208 Pt—land based farm, 11,996 Pt—offshore wind power plant) have a particularly significant impact on the value of this index. Higher level of nonfunctional impact was found for a land-based wind power plant (processes connected with land use, extraction of minerals and fossil fuels), for all the three categories (Figure 4).

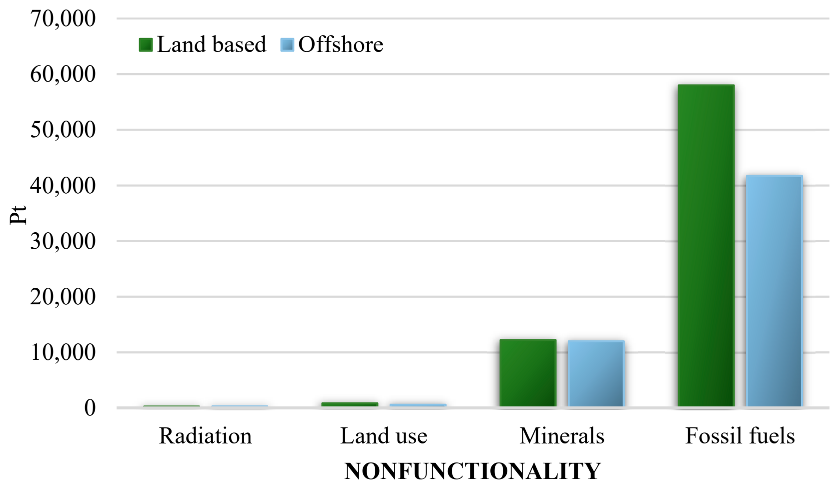

Figure 4. Results of grouping and weighing environmental impacts for nonfunctional impacts involved in life cycles of land-based and offshore wind power plant. Authors' own research.

The value of nonecological impact of the land based and offshore wind power plant includes eight categories. The one, characterized by the highest level of impacts involves the fossil fuels extraction processes (58,004 Pt—land based wind fam, 41,713 Pt—offshore wind power plant) and processes of minerals extraction to a smaller degree (12,208 Pt—land based wind power plant, 11,996 Pt—offshore wind power plant), emission of compounds which cause the climate change (9138 Pt—land based wind farm, 9875 Pt—offshore wind power plant) and substances with ecotoxic properties (9860 Pt—land based wind power plant, 10,297 Pt—offshore wind power plant). The offshore wind power plant was characterized by a higher value of the nonecological impact index (as compared to land-based wind power plant), for three categories: emission of radioactive elements, emission of ecotoxic compounds, and emission of substances that contribute to global warming (Figure 5).

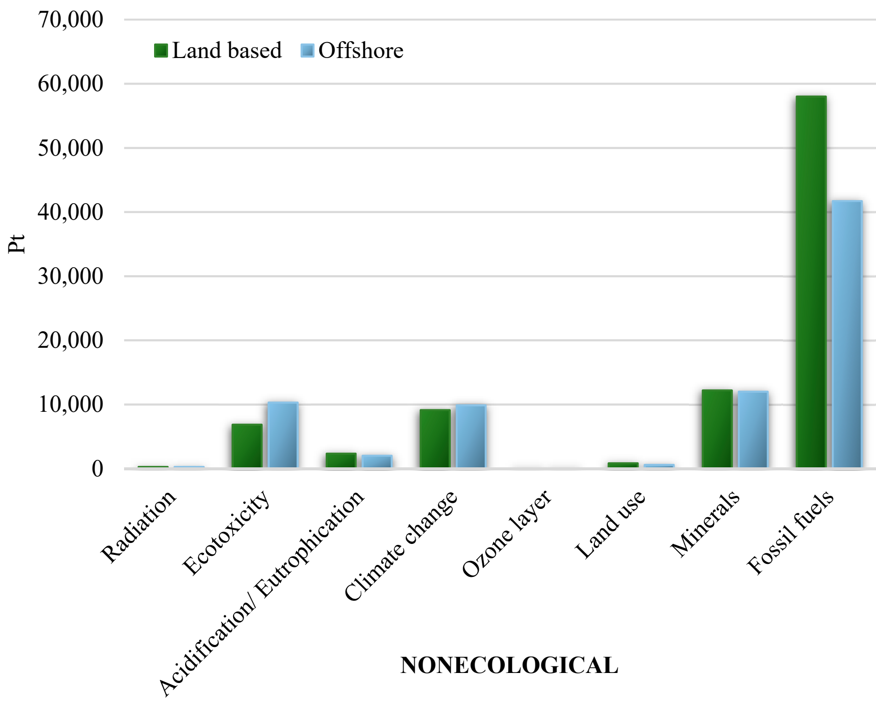

Figure 5. Results of grouping and weighing the environmental effects for ecological impacts involved in land and offshore wind power plant life cycles. Authors' own research.

Nonsozological impact is characterized by four impact categories. Two of them have the highest influence on the value of this index: processes connected with extraction of fossil fuels (58,004 Pt—land wind power plant, 41,713 Pt—offshore wind power plant) and minerals (12,208 Pt—land wind power plant, 11,996 Pt—offshore wind power plant). According to the three assessed impact categories, it was the land wind power plant which was found to be characterized by a higher level of nonsozological impact (processes connected with utilization of the land, extraction of minerals, and fossil fuels) (Figure 6).

Upon analyzing the impact of all the categories, which occur in the Eco-indicator 99 model, on reduction of benefits and an increase in ecological cost, one can notice that two of them have a particularly significant influence on the value of the impact indexes—fossil fuel extraction processes (area: resources) and harmful emission causing respiratory diseases (area: human health). The offshore wind power plant has a larger negative impact on the environment for five out of the eleven of the analyzed categories (i.e., emission of cancerogenic substances, organic compounds causing respiratory system diseases, climate changing compounds, radioactive elements, and ecotoxic substances) (Figure 7).

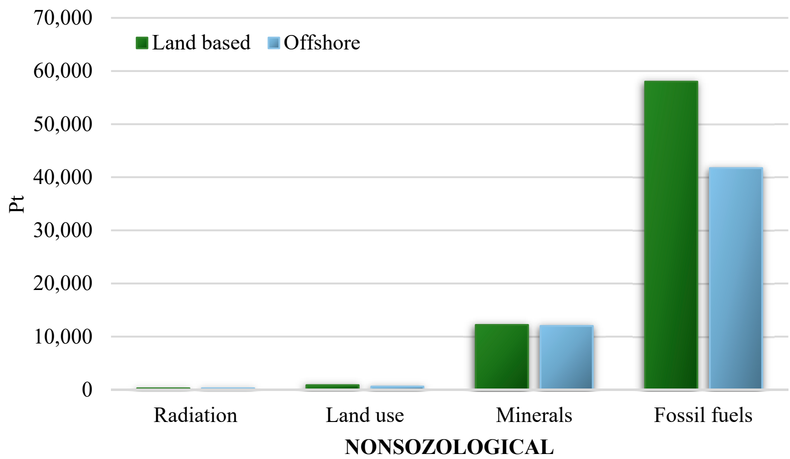

Figure 6. Results of grouping and weighing environmental impact for nonsozological impacts, occurring throughout land and offshore wind power plant life cycles. Authors' own research.

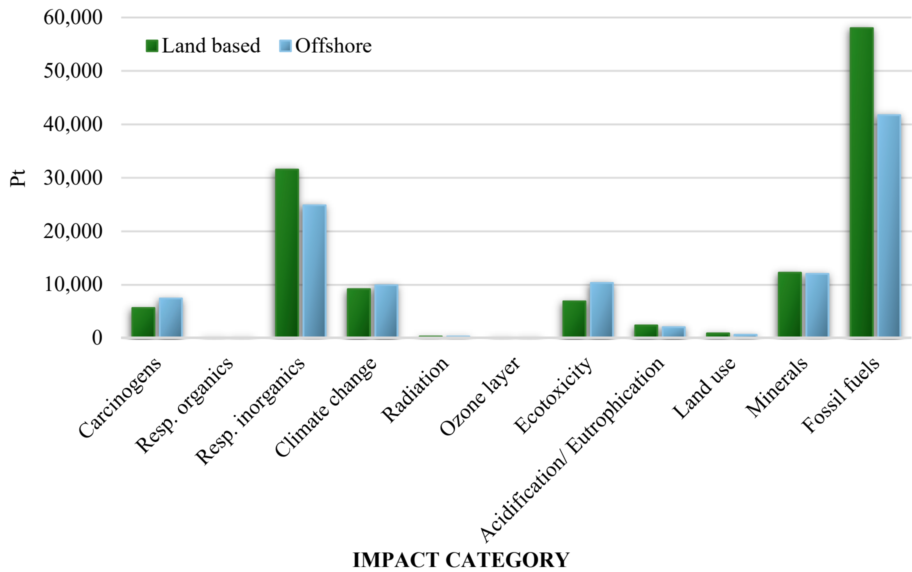

Figure 7. Results of grouping and weighing the environmental effects for the type of impact caused by operation of land and offshore wind power plant cycles. Authors' own research.

A comparative analysis of the impact values of indexes, for four impacts types, shows that the most negative impact was reported for the area of ergonomic impact (115,357 Pt—land-based wind farm, 97,166 Pt—offshore wind power plant) and ecological impact (89,681 Pt—land-based wind power plant, 76,784 Pt—offshore wind power plant). The harmful impact of a land wind farm on its environment was found to be higher in each area, as compared to an offshore wind power plant (Figure 8).

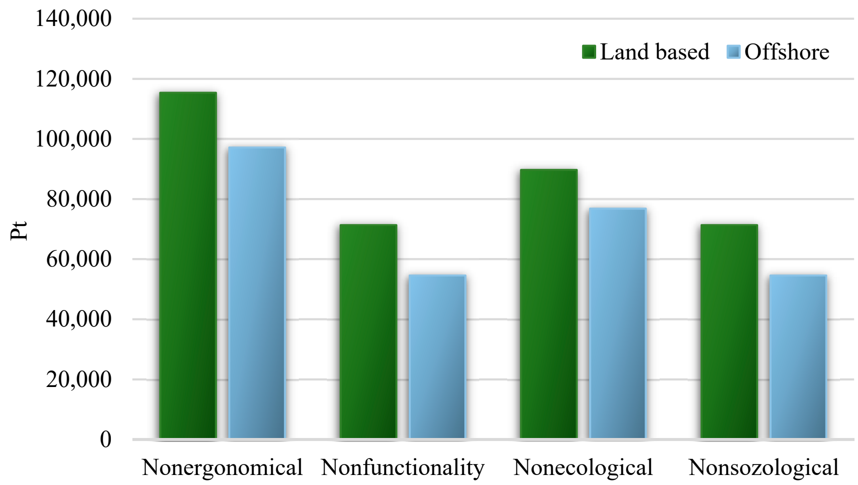

Figure 8. Results of grouping and weighing environmental effects for types of impacts, occurring in life cycles of land-based and offshore wind power plants. Authors' own research.

Land wind power plants pose a significant threat to its operators' health (46,591 Pt) and processes connected with fossil fuels exhaustion (70,212 Pt), whereas offshore wind power plants cause more adverse effects on the quality of the environment (12,905 Pt). In the three fields of impact, both kinds of power plants pose the biggest threat on natural resources and human health (Figure 9).

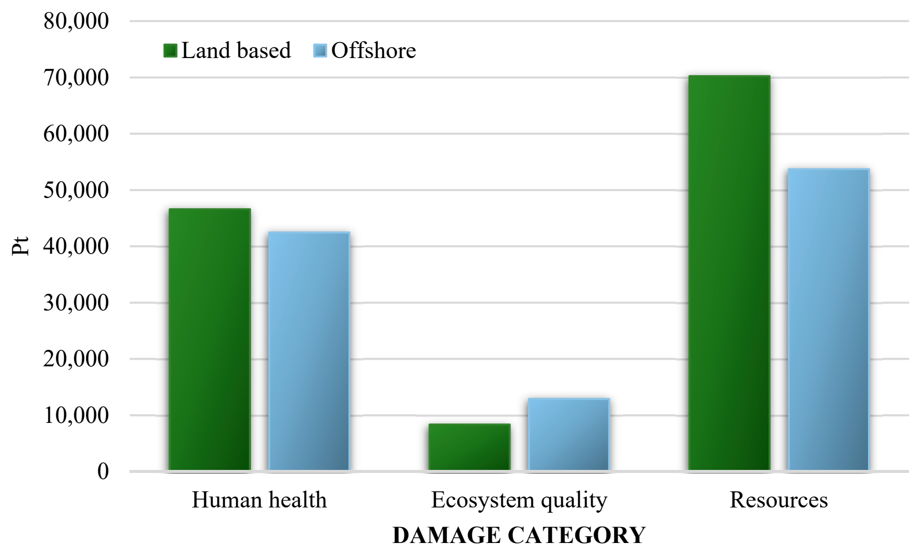

Figure 9. Results of grouping and weighing environmental effects for impact areas occurring in life cycles of land-based and offshore wind power plants. Authors' own research.

Figure 10 presents the results of grouping and weighing environmental consequences of the most important components of land-based and offshore wind power plants, for all impact categories. The highest level of negative impact on the environment, in both cases, is characteristic of the tower and foundations of the wind power plant. The nacelle, rotor, and tower are found to be the most cost consuming for the offshore power plants, while foundations are for the land-based power plant.

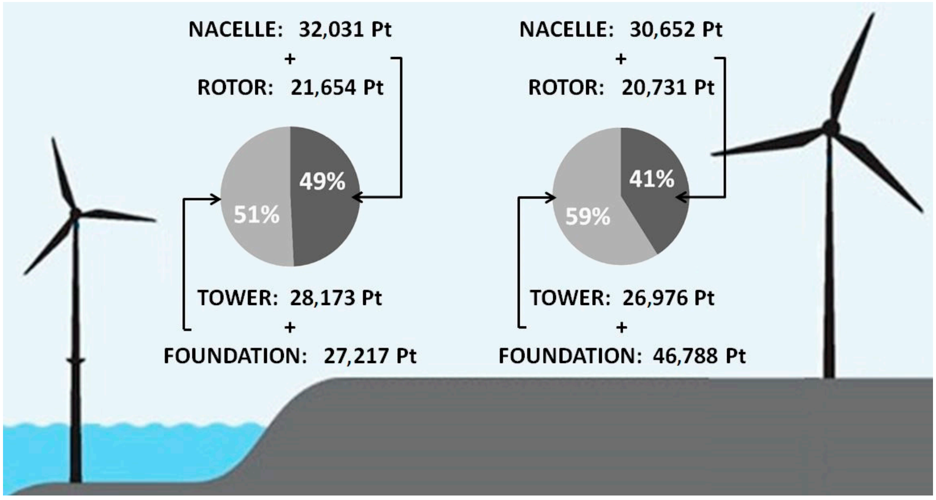

Figure 10. Results of grouping and weighing environmental effects of the most important elements of land-based and offshore wind power plants for all categories of influence. Authors' own research.

As a result of grouping and weighing the environmental effects that occur throughout land and offshore wind power plant life cycles, it was found that a land-based wind farm is a source of more adverse impact (125,147 Pt) compared to its marine equivalents (109,075 Pt) (Figure 11).

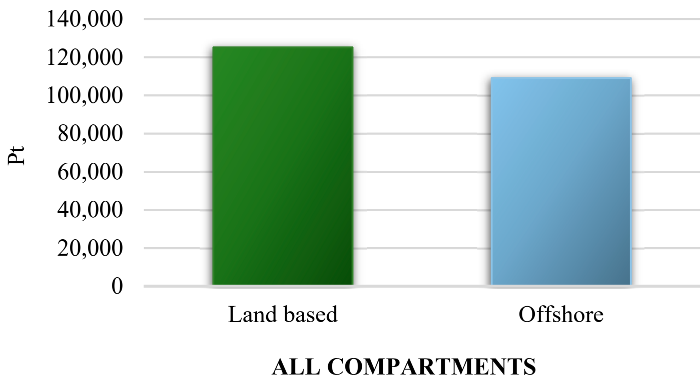

Figure 11. Results of grouping and weighing environmental effects occurring in life cycles of land-based and offshore wind power plants. Authors' own research.

The works available in the field of offshore and onshore wind farms fail take into consideration the issues of nonergonomics, nonsozology, nonecology, and nonfunctionality. The analyses refer mainly to CO_2 emission in the life cycle [34–36] in terms of criteria which are diametrically different from those presented in this study. The obtained results are consistent with the previous results presented in References [34,37] that refer to a completely different approach to the issue of environmental impacts that is commonly used in LCA methods.

4. Summary and Conclusions

The main goal of the study was accomplished with the use of a comparative analysis regarding the environmental impact of the land and offshore wind power plants' life cycle.

The subject of this study were 2-MW land and offshore wind power plants (manner of anchoring were a monopile type) and assessment of the life cycle with the use of the LCA method and Eco-indicator 99 modelling that enabled numerical determination of impacts values of a technical system for four factors: nonergonomics, nonfunctionality, environment friendliness, and nonsozological impact.

The most harmful impact found for nonergonomics (115,357 Pt—land wind power plant, 97,166 Pt—offshore wind power plant), ecological impacts (89,681 Pt—land-based wind power plant 76,784 Pt—offshore wind power plant). Adverse impact on the environment was higher for a land-based wind power plant in all of the impacted areas as compared to an offshore wind power plant.

The processes connected with fossil fuel extraction and emission of compounds causing respiratory diseases have the largest influence on the value of impacts. Land-based wind power plants pose a significant threat to the operators' health (46,591 Pt) and the fossil fuel extraction processes (70,212 Pt), whereas the offshore ones cause more adverse effects on the environment (12,905 Pt).

The particularly high share of the impact of land wind power plant foundations on the environment (46,788 Pt) prompts the search for new materials and technological solutions to be used in the foundation of such large technical facilities.

A life cycle assessment of a land-based wind power plant found it to be a source of a significantly larger amount of adverse impact (125,147 Pt) on the environment as compared to an offshore wind power plant (109,075 Pt). It needs to be mentioned that the results may differ depending on the manner of an offshore wind power plant anchoring.

In light of the analyses on the impact of wind farms on the environment, it seems necessary to undertake further research in order to design/develop and implement an algorithm to address all the issues connected with utilization of wind farm materials, elements, and systems after the end of its functioning, including environment-friendly recycling processes. Apart from the need to undertake further research on the environmental impact of technical objects, it is important to promote this idea.

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