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# Analysis of Environmental and Energetical Possibilities of Sustainable Development of Wind and Photovoltaic Power Plants

# Analiza ekologiczno-energetycznych możliwości zrównoważonego rozwoju elektrowni wiatrowych i fotowoltaicznych

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## Abstract
The study evaluated the ecological and energetical possibilities of sustainable development of wind and photovoltaic power plants using the LCA method. An environmental analysis of the material phases of the life cycle of the 2 MW wind and photovoltaic power plant was conducted. The size of the environmental impacts over the life cycle and the scale of emissions of hazardous substances into the atmosphere, water and soil have been analyzed. Particular attention has been paid to greenhouse gas emissions and energy intensity levels recorded at various stages of the life cycle. The research conducted has provided the basis for formulating recommendations and guidelines for more pro-environmental, sustainable development of the analyzed renewable energy sources.

**Key words:** renewable energy sources, sustainable development, wind power plant, photovoltaic power plant, Life Cycle Assessment (LCA)

## Streszczenie
W artykule dokonano oceny ekologiczno-energetycznych możliwości zrównoważonego rozwoju elektrowni wiatrowych i fotowoltaicznych, z wykorzystaniem metody LCA. Przeprowadzono środowiskową analizę materialnych faz cyklu istnienia 2 MW elektrowni wiatrowej i fotowoltaicznej. Przeanalizowano wielkość następstw środowiskowych w ich całym cyklu życia oraz skalę emisji niebezpiecznych substancji do atmosfery, wody i gleby. Szczególną uwagę zwrócono na emisję gazów cieplarnianych oraz poziom energochłonności odnotowany w poszczególnych etapach cyklu istnienia. Przeprowadzone badania stały się podstawą do sformułowania zaleceń i wytycznych do bardziej prośrodowiskowego, zrównoważonego rozwoju analizowanych odnawialnych źródeł energii.

**Słowa kluczowe:** odnawialne źródła energii, zrównoważony rozwój, elektrownia wiatrowa, elektrownia fotowoltaiczna, środowiskowa ocena cyklu istnienia (LCA)

## Introduction

Technical objects, like living organisms, are subject to certain changes in their life cycle. The existence of each object is cyclical, starting with design, manufacturing, use, post-mortem planning. Because of this similarity, for all machines and equipment, including renewable energy sources, the term *life cycle* applies. The life cycle of the renewable energy system consists of two intangible phases (formulation of need, construction) and three material (production, exploitation and post-use managment) (Mroziński, Piasecka, 2015, Piasecka, 2013, Twidell, Weir, 2015).

The principle of sustainable development is favoring rapid socio-economic development with an increase in the quality of life of the population together with a simultaneous improvement of the natural environment.

One of the main problems of sustainable development is energy supply and it's major importance in the socio-economic development of the European Union. In Poland, where dominant energy production is based on fossil fuels, this problem is particularly important (Lynn, 2010).

The undisputed advantage of renewable energy is the positive environmental impact of reducing emissions to the atmosphere, including greenhouse gases. The development of this sector causes a clear reduction in the external (environmental) costs that occur with conventional energy technology, and this has a positive effect on the economy and society. Renewable energy is also a leading and prospective technology for combating global warming and one of the most important challenges in the development of modern civilization (Ackermann, 2005; Elbaset, Hassan, 2017; Luque, Hegedus, 2008; Mroczek et al., 2013). Until recently, in the economic sphere of human interest, there were mainly the first three stages of the life cycle of renewable energy sources - design, manufacture and use. At the heart of the work on minimizing the environmental impact of the life cycle of industrial products lies LCT (Life Cycle Thinking), the concept of thinking in terms of life cycle and on top of that it's one of the concepts recommended by the European Commission. In order to achieve sustainable development, it is necessary to improve the manufacturing processes by reducing the harmful environmental impact of the processes themselves and the products produced. At present, the EU stimulates mechanisms that promote the introduction of more environmentally-friendly products and, in the long term, the improvement of the European environment and Europe's better position in the world. The concept of seeking ways to minimize the environmental impacts of products and services throughout their life cycle is in line with the adopted European Commission policy. The main assumption is that interventions are mainly at the stages of the life cycle where the greatest negative impact on the environment is achieved (Dincer et al., 2014; Han et al., 2014; Patel, 2006; Richter et al., 2013; Tiwari, Mishra. , 2012).

As a consequence, the assessment of the environmental and energy sustainability of wind and photovoltaic power plants using the LCA method was adopted as the main objective.

## Material and methods of analysis

The main assumption of the study was the implementation of a comprehensive analysis of the life cycle of two different types of renewable energy sources (wind and photovoltaic) using an Life Cycle Assessment (LCA) to formulate recommendations and guidelines for more pro-environmental, sustainable development of analytical objects.

LCA (Life Cycle Assessment) is a management process technique designed to assess potential environmental hazards. The essence of the method is to focus not only on the evaluation of the final outcome of a given technological process, but also on the assessment and evaluation of the consequences of the whole process for the environment. According to the ISO 14000 standard, the LCA assessment consists of four successive key elements: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation (Frankl, 2002, Piasecka, Tomovsky, 2013; Traverso et al., 2012).

The study compiles a comparative analysis of two renewable energy systems with installed capacity of 2 MW – terrestrial, three-blades wind turbine with horizontal axis of rotation and photovoltaic power station built of policrystalline modules. LCA analysis will be used to determine whether there are differences in the size of the impact on the environment generated during the life cycles of selected renewable energy sources working on two different technologies. The evaluated systems were manufactured by companies with a leading position on the global and European market.

The analysis is intended primarily to describe the existing reality (LCA retrospective), but also to model future developments, to make recommendations for developing more pro-environmental (LCA prospective) solutions. The proceeding will be a classic LCA trial. Most of the processes carried out in the analyzed cycles of the life cycle of wind and photovoltaic power generation (production, exploitation, post-use management) take place in Europe. As the main premise of the analysis is to show the differences in environmental impacts resulting primarily from changes in technologies used to generate electricity, the geographic and temporal scope of the data is the same, while the technological scope is different. Geographic scope is Europe. Time ranges cover the same 25-year exploitation period (Guinée, 2002; Klöpffer, Grahl, 2014).

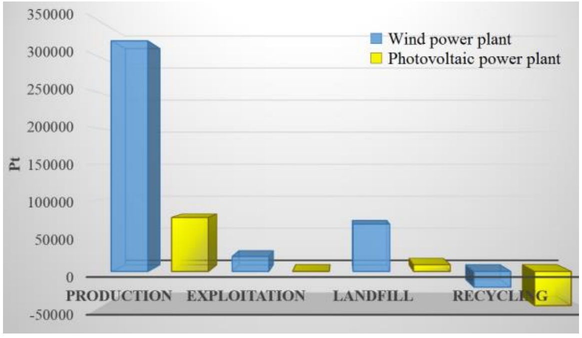
All restrictions and exclusions were made in parallel for all product systems. The analysis skips the stage of storage, sales, and distribution for both technologies analyzed. As a result, product systems were equally affected by the same simplifications that introduced similar levels of uncertainty. The exclusion criterion was less than 0.01% of the share of both life-cycle and environmental impact at the level of life cycle of both renewable energy installations in question.

The analysis can be classified as bottom-up. The level of advancement classifies it in detailed analysis. The data used in the study was obtained from manufacturers or downloaded from the SimaPro database. Due to the conclusion of confidentiality agreements with companies producing wind turbines

and photovoltaic power plants, detailed information on the construction of research facilities and technological data are not disclosed in this study.
Impact assessment was done using the SimaPro 8.1 computational program. Developed by the Dutch company PréConsultants. As the basic calculation procedure, the Eco-indicator 99 method was based on the endpoints of the environmental mechanism. This method allows to receive results on six aggregation levels, including a single value of the escapement. Due to the lack of clear exclusion criteria, all the categories of influence within Eco-indicator 99 are analyzed. The results of the characterization of the impact areas indicators are analyzed by normalization, grouping and weighing into the final eco-indicator. Carrying out the weighing process allowed us to obtain results at environmental points (Pt). A thousand environmental points are equal to influence of one European per year (Bare et al., 2000; Jungbluth et al., 2005; Klinglmair et al., 2014).
With LCIA were also conducted additional analyzes using CED and IPCC models. The CED (Cumulative Energy Demand) method has been used to determine the cumulative energy demand. The IPCC (Intergovernmental Panel on Climate Change) methodology has allowed for a quantitative assessment of the greenhouse gases (GHG) on greenhouse effect with relation to carbon dioxide (Dreyer et al., 2003; Guinée et al., 2011). Stichnothe et al., 2014).

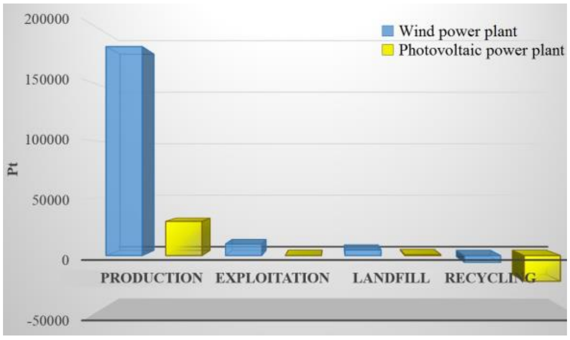
## Results and their discussion

Picture 1 shows the results of grouping and weighing the environmental consequences of the material life cycle of the wind and photovoltaic plants. In both cases, the stage of production is the source of the greatest amount of negative impact on the environment (wind power plant: 322461 Pt, photovoltaic power plant: 75538 Pt). For all lifecycle stages, the wind turbine has more harmful effects compared to a photovoltaic power plant with the same installed capacity. The use of recycling processes would reduce the destructive impact of the remaining life cycle of the two renewable energy systems analyzed (wind power plant: -21978 Pt, photovoltaic power plant: 47608 Pt).
A detailed analysis of the environmental consequences of the life cycle of both renewable energy systems shows that both installations are the source of the highest levels of harmful emissions to the environment in the field of inorganic compounds causing respiratory diseases, fossil fuel and mineral mining processes and emissions of compounds that cause climate change of ecotoxic character. Re-use of plastics, materials and elements of wind and photovoltaic power plants in the form of recycling would reduce the environmental impact of earlier stages of the life cycle, particularly the impact of fossil fuel and mineral mining processes and emissions of inorganic compounds causing respiratory and carcinogenic diseases (table 1).



Picture 1. Results of grouping and weighing of environmental impacts occurring in the material life cycle of wind and photovoltaic plants (own research)

Throughout the material life cycle of technical objects, harmful emissions can be noted in the atmospheric, aquatic and soil environments. The largest amount of hazardous substances gets into the atmosphere, the smallest amount into soil. In the case of wind turbine and photovoltaic plants the most harmful compounds entering the atmosphere are emitted during the production of plastics, materials and components of these systems (wind power plant: 181994 Pt, photovoltaic power plant: 29743 Pt). Wind power installation is a source of major negative environmental impacts in all stages of its life cycle (picture 2).



Picture 2. Results of grouping and weighing environmental impacts on atmospheric emissions in the material life cycle of wind and photovoltaic plants (own research)

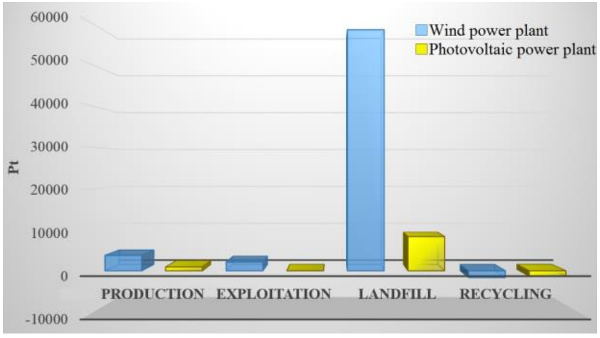
In the case of negative emissions to the aquatic environment, the particular risk is the possibility of storing waste materials, materials and elements of wind turbines in the landfill that are no longer usable (58601 Pt). This post-use management option also poses a major environmental risk for the photovoltaic power plant (8302 Pt) (picture 3).
The distribution of the negative impacts of the various stages of the life cycle of wind and photovoltaic plants on the soil environment is clearly correlated with the emission distribution to the atmospheric environment. The largest share was also recorded for manufacturing processes and in this case, the amount

Table 1. Results of grouping and weighing environmental impacts occurring in the material life cycle of wind and photovoltaic power plants, including impact categories (own research)

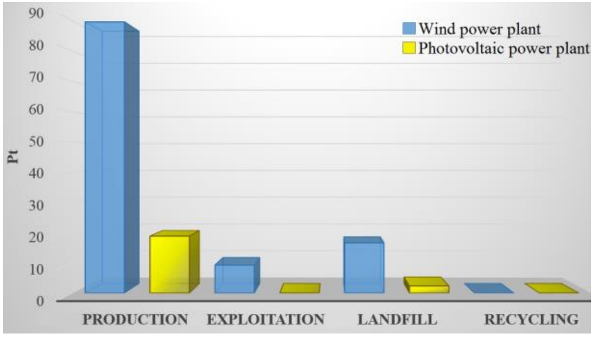
| Impact category | Production | | Exploitation | | Landfill | | Recycling | |
|---|---|---|---|---|---|---|---|---|
| | Wind power plant | PV power plant | Wind power plant | PV power plant | Wind power plant | PV power plant | Wind power plant | PV power plant |
| Carcinogens | 4398.95 | 1145.77 | 2076.24 | 6.06 | 30181.07 | 5307.32 | -1550.69 | -1649.87 |
| Resp. organics | 55.82 | 22.57 | 4.35 | 0.01 | 9.91 | 1.47 | -13.22 | -34.43 |
| Resp. inorganics | 143145.90 | 21699.35 | 6607.17 | 21.28 | 693.94 | 144.18 | -2793.50 | -14845.80 |
| Climate change | 10957.79 | 4111.80 | 2397.00 | 6.71 | 4129.33 | 584.17 | -2861.01 | -5371.96 |
| Radiation | 376.18 | 56.56 | 6.24 | 0.05 | 5.81 | 1.28 | 0.00 | 0.00 |
| Ozone layer | 22.83 | 4.06 | 0.31 | 0.00 | 0.12 | 0.03 | -1.70 | -8.34 |
| Ecotoxicity | 15513.35 | 1712.20 | 393.02 | 1.46 | 28434.53 | 3014.25 | 127.02 | -801.90 |
| Acidification/ Eutrophication | 11542.72 | 1952.00 | 643.22 | 1.53 | 96.66 | 15.66 | -422.94 | -1003.13 |
| Land use | 2605.56 | 1364.47 | 308.86 | 0.73 | 227.80 | 36.30 | 0.00 | 0.00 |
| Minerals | 45664.61 | 18966.73 | 1040.09 | 17.50 | 37.24 | 4.05 | -1116.57 | -3776.93 |
| Fossil fuels | 88176.03 | 24503.52 | 7478.53 | 8.27 | 2372.73 | 273.40 | -13344.06 | -20116.44 |
| **Total** | **322459.74** | **75539.04** | **20955.02** | **63.60** | **66189.12** | **9382.10** | **-21976.68** | **-47608.81** |

**Table 2.** Results of grouping and weighing environmental impacts on compounds and processes affecting human health, environmental quality, and raw material resources in the material life cycle of wind and photovoltaic power plants (own research)

| Category | Production | | Exploitation | | Landfill | | Recycling | |
|---|---|---|---|---|---|---|---|---|
| | Wind power plant | PV power plant | Wind power plant | PV power plant | Wind power plant | PV power plant | Wind power plant | PV power plant |
| Human health | 158957.47 | 26743.48 | 11091.31 | 35.29 | 35020.18 | 6030.17 | -7220.12 | -21628.06 |
| Ecosystem quality | 29661.63 | 6732.27 | 1345.10 | 3.71 | 28758.99 | 3092.29 | -295.93 | -1868.84 |
| Resorces | 133840.64 | 43186.70 | 8518.61 | 25.23 | 2409.96 | 273.16 | -14460.63 | -23966.27 |



Picture 3. Grouping and weighing results of environmental impacts on the aquatic environment in the material life cycle of wind turbines and photovoltaic (own research)

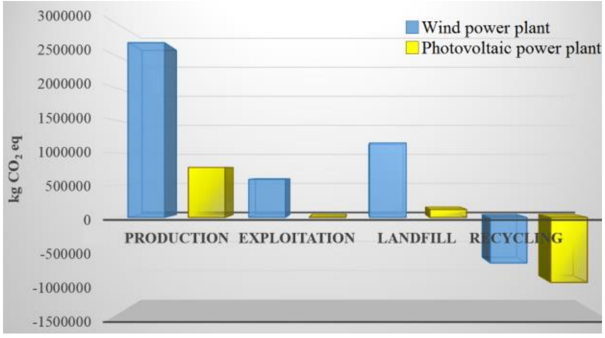


Picture 4. Results of grouping and weighing environmental consequences for emissions to the soil environment occurring in the material life cycle of wind and photovoltaic plants (own research)

of harmful influence exerted on the environment by the wind power plant is higher than that of the analogue solar energy installation (picture 4).

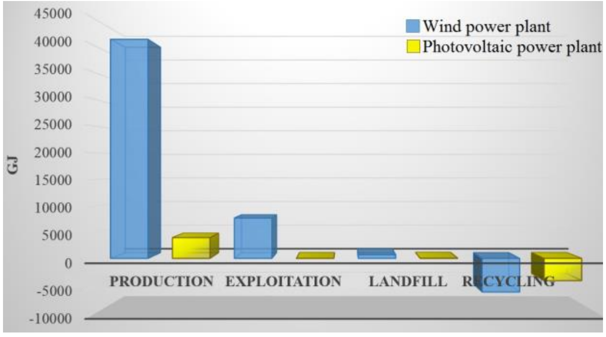
Of the three main areas of negative impact of the life cycle of the analyzed technical objects, the highest level of harmful influence was characterized by the stage of production. In the case of wind turbines, the most destructive environmental consequences were recorded in the area of human health deterioration (158958 Pt), while for photovoltaic power plants – the depletion of raw materials (43187 Pt). It is also evident that the impact of the photovoltaic installation (from 4 to 35 Pt) is very low (table 2).

Use of the IPCC methodology analysis allowed a detailed analysis of the amount of greenhouse gases emitted to the atmosphere at different stages of the life cycle of wind and photovoltaic power plants. The largest source of harmful emissions was the production stage (wind power plant: 2700558 $CO_2$eq, photovoltaic power plant: 773455 $CO_2$eq). During the lifecycle of a wind power installation, more greenhouse gases are emitted compared to the life cycle of the photovoltaic system (picture 5).




Picture 5. Assessment of greenhouse gas emissions for material life cycle of wind and photovoltaic power plants using the IPCC method (own research)

Supplementing the research on the life cycle impact of selected renewable energy sources on the environment was an energy consumption analysis carried out using the CED method. The largest demand for energy for both wind and photovoltaic plants was recorded at the manufacturing stage (wind power plant: 41558 GJ, photovoltaic power plant: 3937 GJ). Much more energy-intensive is the material stages of the life cycle of the wind energy system compared to photovoltaic systems. The use of recycling processes in the area under consideration shows a higher level of efficiency in the management of plastics, materials and components of photovoltaic power plants (picture 6).




Picture 6. Assessment of energy consumption of the material life cycle of wind and photovoltaic power plants using the CED method (own research)

## Summary and conclusions

The source of sustainable development of each country and region is the rational use of natural resources and energy. Particularly unfavorable effects on the environment are the processes of extraction and processing of fossil fuels that are energy carriers. Coal-based conventional energy is one of the main consumers of environmental resources, causing land degradation and the effects of consumption like soil and water pollution and significant emissions into the atmosphere of combustion products. An alternative source of sustainable energy supply should be renewable energy (Kaltschmitt et al., 2013; Mohnaty et al., 2016; Velkin, Shcheklein, 2017).

The main objective of the study was achieved by evaluating the ecological and energetic opportunities for sustainable development of wind and photovoltaic power plants using the LCA method.

Life cycle analysis of 2 MW of wind and photovoltaic power plants using the Eco-indicator 99, IPCC and CED models, allows the following conclusions to be drawn:

1) For all life cycle stages, the wind turbine has more negative environmental impacts compared to a photovoltaic power plant with the same installed capacity.
2) The production stage is the source of the greatest amount of harmful environmental impacts in both life cycles.
3) The use of recycling processes would reduce the destructive impact of the remaining life cycle of the two renewable energy systems analyzed.
4) The largest amount of hazardous substances arising in the life cycle of both evaluated systems gets into the atmospheric environment, the smallest to the soil.
5) The largest source of greenhouse gas emissions in both cases was the stage of production. During the lifecycle of a wind power installation, more greenhouse gases are emitted compared to the life cycle of the photovoltaic system.
6) The highest energy demand for both power plants was recorded at the manufacturing stage. Much more energy-intensive is the material stages of the life cycle of the wind energy system compared to photovoltaic systems.

On the basis of the life-cycle research of wind and photovoltaic power plants, in terms of pro-environmental sustainability of renewable energy plants, it is proposed to:

1) reduce the negative impact on the environment of production processes by implementing modern technologies that are less energy-intensive, material-intensive and emissive of hazardous substances;
2) creation of a pro-environmental algorithm for dealing with plastics, materials and power plant components at the end of their operation, taking into account primarily the recycling processes;
3) work on more environmentally-friendly, sustainable construction materials that will simultaneously maintain appropriate mechanical, technical and quality parameters;
4) a construction that makes it easier to separate individual materials that are easy to identify during post-use management;
5) popularize the idea of research and assessment of the impact of technical objects throughout their life cycle;

6) popularize the idea of LCT (Life Cycle Thinking), leading to sustainable development of renewable energy systems.

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