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JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2022.140385
2022, No. 52 (I–III): 156–165

Simulation of the influence of wind power plants on the compartments of the complex landscape system

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RECEIVED 24.11.2020 REVIEWED 15.12.2020 ACCEPTED 16.07.2021

Abstract: The impact of wind power plants on the environmental components is assessed taking into account a number of their parameters, in particular the technical characteristics of wind turbines, the characteristics of networks, engineering and other structures. To do this the life cycle of the wind power plants is described taking into account (by way of inventory) all the necessary materials and resources. Waste management scenarios have been developed, the use of which will make it possible to reduce the harmful impact on the environment. Based on the inventory and input data on the wind farm under study, a diagram is generated – a tree of life cycle processes of the wind power plant – to determine the potential environmental impacts. A list of impact categories that represent the load on the environment caused by the wind power plant is defined; also, the relative contribution of harmful factors is determined for each category, taking into account possible scenarios of waste management. Ecological profiles have been built for all potential impacts on the environment. After normalisation and determination of significance, individual estimates of all indicators and their distribution in three categories of lesions were obtained: human health, ecosystem quality and resources, as well as four stages of the wind farm life cycle: production, dismantling and disposal, operation, transportation and installation. The obtained profiles made it possible to determine individual indicators and eco-indicators, expressed in eco-points that characterise the wind farm under study.

Keywords: eco-indicators, ecological profile, environmental impact assessment, harmful factor, simulation modelling, waste management, wind power plant, wind turbine

INTRODUCTION

Human activities in the process of manufacturing products or providing services are inevitably associated with the environmental impact. Depending on the nature of the product/service, environmental impacts may be different, such as the ozone layer depletion, greenhouse effect, soil acidification or biodiversity loss, and so on. Each product or service goes through a series of development stages which collectively make up their life cycle (LC) and each of the stages has its own specific impact on the environment.

Earth is a closed system of material flows. Moving from one product to another and changing the shape of its state, matter circulates in the ecological system. That is why the total mass of matter does not change, regardless of what humanity produces on Earth, or what service it provides, and the course of material flows and processes occurs in a linear fashion. Thus, over an infinitely long period of time, materials that have passed through the technosphere are returned to the environment again as raw materials.

The life cycle concept considers products/services from the beginning of their physical emergence until the moment of their termination. The life cycle consists of the following stages: raw material extraction, energy production, transportation, primary processing operations, direct product production, packaging, distribution, recycling and others.

In the process of planning and designing the life cycle of a certain product/service, a systematic approach should be applied that takes into account the interaction of this life cycle with the life cycle systems of other products/services. The output energy flows can be both waste of the system under study and serve as resources (input flows) to another system. At all stages of the product/service LC, when energy is used and materials are processed, a certain environmental pollution occurs.

Optimal management of ecosystem conditions involves the use of advanced technologies in their research which are based on the application of modern expert intelligent information systems. Sustainable development of the region as an integral socio-ecological-economic system requires an adequate apparatus informing on the state of the natural environment and the corresponding imitation models. At the same time, prediction should be based on reliable methods for modelling the assessment of ecosystem conditions, which has become the subject of this study.

In recent decades, humanity has faced two conflicting energy problems. On the one hand, this is ensuring the reliability of energy supply, and on the other hand, the prevention of negative effects of energy production on the environment, both in areas where the sources of generation are located and on a global scale [Babak *et al.* 2020; Bosak *et al.* 2019; Cherniuk *et al.* 2020; Prokopenko *et al.* 2017].

It is common belief that the use of electrical energy from renewable sources is environmentally friendly. This is not entirely true, since such energy sources have a fundamentally different spectrum of environmental impact compared to traditional energy sources based on different types of fuel, and in some cases the influence of the latter may be even less dangerous.

The environmental impact of non-traditional and renewable energy sources on the environment has been investigated to a much lesser extent today than the technical issues of their use, especially with regard to their temporal aspect [Burton *et al.* 2001; Chmielniak 2008].

The problems of modelling environmental processes and systems at various levels have been investigated by many domestic and foreign scientists. However, the analysis of the literature sources has revealed that alternative energy issues are mainly addressed in technical terms by studying the further improvement of the design and technology of the use of wind power plants (wind turbines), or from the economic point of view considering the economic effectiveness of using wind energy, while the effects of wind energy on environmental components have not been sufficiently covered and are hardly considered in environmental research.

Practice shows that in order to develop such a methodology that could be used to study and model any ecosystems and their states in different regions, an integrated approach should be applied. In particular, this may be the Life Cycle Assessment (LCA) method, based on a series of ISO standards [ISO 14040, 1997; ISO 14042: DSTU ISO/TR 14047:2007, 2009; DSTU ISO 14040:2004, 2007] and which is one of the leading methods for assessing the potential environmental impacts of wind power stations (wind farms). This approach was used in the studies of European scientists [Cleary *et al.* 2012; Ghenai 2012; Martinez *et al.* 2009; Tóth, Szegedi 2007], as well as one of the largest manufacturers of wind turbines – the Danish company Vestas [Vestas 2005]. Not many current life cycle assessment studies exist for wind turbines with high rated power (600 kW). The available studies [Bojko *et al.* 2019] are differing in their scope, but show the dominant influence of the material production on the environmental performance of wind power plants. Some of these assessments also indicate large amounts of indirectly produced waste.

The purpose of the study is to develop a methodological approach to the construction of an integrated system of indicators for assessing the effects of wind turbines on the layers and subsystems of compartments of complex landscape systems (CLS) at all stages of their life cycle (LC) as well as through using simulation.

The object of the study were 34 wind turbines (WT) of the company Siemens SWT DD-142 in the wind farm with a total capacity of 120 MW with the necessary infrastructure, namely access roads, 110 kV underground cable power lines and 35 kV underground cable networks, distribution points and a substation, with a total area of 30.6041 ha, the Atlas Volovets Energy LLC being part of the wind park. The site of the Volovets wind farm is located in the northwest of the Transcarpathian region within the boundaries of the Borzhava Polonyna of the Eastern flysch Carpathians.

The subject of the study is CLS in which wind turbines operate. CLS is a biological system characterised by the structural and functional unity of the interconnected components and the integrity of the biotic and abiotic components. The biotic component of the environment is integrated into compartments consisting of subsystems of different levels of organisation and a large number of different layers, between which there are close material, energy, and hierarchical connections. The Borzhava Polonyna of the Eastern flysch Carpathians, by definition of Goedkoop *et al.* [2016], is referred to as CLSs.

Considering the environmental factor is today one of the most important conditions for the life of not only industrial systems of various purposes, such as wind farms, but also of society in general. Sustainable development is first and foremost the conservation and rational use of natural resources. That is why the environmental component should be considered as one of the determining factors in solving the problems of achieving sustainable development and an acceptable level of economic security of both individual business entities and regions and the state as a whole. It can be characterised by a variety of forms of manifestation of environmental impacts, the composition and intensity of environmental impacts, the nature of the social, economic, physiological and other consequences of these impacts.

To quantify the consequences of wind turbine impacts in the CLS compartments, the life cycle of wind turbines was analysed using SimaPro software which is a professional tool for collecting, analysing, and monitoring the environmental characteristics of products and services. With its help, it is possible to model and analyse complex LCs in a systematic and understandable way.

In particular, SimaPro makes it possible to analyse products taking into account waste management scenarios which can be modelled independently, depending on the selected product/service. The LC contains waste management scenarios with percentages for each stage (for example, recycling, landfilling, etc.) in a general scenario or one scenario for landfilling.

To analyse the environmental impact of a wind turbine in the CLS compartments during its LC, the SimaPro program contains data on the individual components of the wind turbines in the CLS compartments, indicating the materials, components and processes that accompanied them. All the necessary input data were grouped by the relevant stages of the wind turbine life cycle, namely: production – contains the production of raw materials (concrete, aluminum, steel, fiberglass, etc.) for the manufacture of components of the turbine; transportation – covers the transportation of materials for the production of WT components, the delivery of components to the installation site during erection works, and the necessary movement of vehicles when equipping a wind farm; installation and erection procedure – includes work on the construction and installation of wind turbines; operation and maintenance – the longest stage, covering the period of the WT operation, oil change and use of vehicles for maintenance; dismantling – provides for the final closure of the wind farm after its operating period and subsequent disposal of the generated waste.

MATERIALS AND METHODS

The ISO 14040 and ISO 14044 standards defines the concept of life cycle assessment as a combination of the comprehensive environmental characteristics of a product, where a quantitative measurement of their environmental friendliness is the result of the LCA process [Goedkoop *et al.* 2016]. In Europe, LCA standards are refined and supplemented by the EU [2010], which ensures greater consistency and objectivity of environmental impact assessments.

The LCA is the basis of such software products as SimaPro, Gabi, Ecoinvent, Umberto, OpenLCA, LCAPIX, BEES 4.0, TEAM, Athena Impact Estimator and others. The leaders among commercial LCA software in Europe today are SimaPro and Gabi [Sinha *et al.* 2016]. The kind of software product to be applied for a particular case, is determined by the analyst based on the goals and the object of study. SimaPro software product, which we will use for LCA, supports EPDs, GHG protocol and ILCD Handbook; it provides for four stages of research:

Stage 1. Determining the goal and scope of the study – beneficiaries and their expectations.

Stage 2. Life cycle inventory – the creation of a LC model, all environmental inputs and outputs being displayed.

Stage 3. Life Cycle Impact Assessment is a study of the importance of all inputs and outputs in terms of their potential impact.

Stage 4. Interpretation of the results obtained [Goedkoop *et al.* 2016].

According to the European standard for environmental impacts caused by wind turbines, there are seven categories of impacts: abiotic depletion – non-fossil resources (ADP-non-fossil, kg Sb eq); abiotic depletion – fossil resources (ADP-fossil, MJ net caloric value); acidification (AP, kg SO_2 eq); eutrophication (EP, kg $(PO_4)_3$ eq); global warming (GWP, kg CO_2 eq); ozone layer depletion (ODP, kg CFC-11 eq); formation of a photochemical ozone layer (POCP, kg C_2H_4 eq) [Pombo *et al.* 2016].

The categories of impact are slightly different for different quantification methods. Nowadays, the following methods are most commonly used in practice: ReCiPe Endpoint (E), Impact 2002, Eco-indicator, EPS system, MIPS concept, etc. [Zbicinski *et al.* 2006]. The categories of harm in many methods are ecosystem quality, human health and the depletion of natural resources. But they can be very specific depending on the needs of the analysis (CO_2 absorption, soil change, fossil fuels, etc.) [Goedkoop *et al.* 2016].

This study uses integrated indicators to assess the impact of wind turbines on CLS compartments over their life cycle. For this, SimaPro offers a wide range of methods and databases which are considered the most recognised and well-grounded for the analysis of such area.

The study include the following steps: defining the background of the problem, functional unit description, building a block diagram of the LC, identifying the boundaries of the system, waste scenario, inventory, generating the process tree, classification, characterisation, normalisation, comparing impacts, determining the environmental index.

Background of the problem. Renewable energy sources are currently rapidly developing, in particular wind energetics, which is the most profitable renewable electric power technology with the fastest growing market and an average cumulative growth of 28% [Kollner, Jungbluth 2000]. Europe accounts for more than 31% of total installed capacity (220,000 MW) and 10% of the annual market growth in recent years. In 2019, wind power supplied 15% of all electricity consumed in Europe.

Electricity generation through wind energy does not have a significant negative impact on the environment and social sphere; in addition, there is a reduction in emissions of greenhouse gases and other harmful substances. According to the estimates of the Institute of Renewable Energy of the National Academy of Sciences of Ukraine (Ukr. Vidnovliuvana enerhetyka Natsional'noi akademiyi nauk Ukrayiny), only due to the planned commissioning of wind power plants with a capacity of 16,000 MW by 2030, the average annual CO_2 emissions will not increase by $32 \cdot 10^9$ kg, and the annual gas saving will amount to $14.4 \cdot 10^9$ m^3.

However, although the wind farm is a renewable energy source and prevents the depletion of natural resources, but, like any object of economic activity, causes changes in the characteristics of the natural landscape and the properties of its components, leading to the formation of technogenic geocomplexes [Lenzen, Wachsmann 2004].

Functional unit. In the study, the electricity generated by one WT during its LC was chosen as a functional unit. According to Vestas [2005], a WT produces ~7.9 $MW \cdot y^{-1}$. With a service factor of 30%, the electricity generated over 25 years will amount to 138.25 $MW \cdot y^{-1}$. This percentage is the amount of energy produced by a wind turbine in one year of the total amount that would be obtained if it were operating at full capacity [SECO 2006]. In general, these values may vary from site to site and through different wind conditions.

System boundaries. An essential task at the 1st stage of the LCA is to identify the boundaries of the system under study, since it is important to discard the impacts that are insignificant for the analysis. Also, the phenomenon of recursion often occurs, that is, energy production needs property and equipment which also have their own LC. To avoid errors, in the practice of the LCA, two approaches are used: fixed assets property and equipment are not considered in the analysis at all, or only the effects from the extraction of raw materials and transportation are taken into account. The bases such as Ecoinvent and USA Input Output account for property and equipment using the second approach. In the LCA, these systems are considered as economic rather than natural. Therefore, carbon sequestration and impact on land use are not considered at all, but environmental pollution by pesticides is taken into account.

The ReCiPe method[1], which is implemented in SimaPro, is based on the principle of balance between natural and economic systems.

The first stage is completed by defining the aim and subject of the study.

The next step in the study, according to the LCA procedure, is describing the life cycle. This requires the following data: information about the object of interest which must be collected by the analyst (foreground data), and background data on physical/chemical dependencies and processes (background data) which are contained in the literature and the Ecoinvent v3 database which is offered together with the SimaPro program.

The inventory phase consists of four steps: building a process tree – in other words, a process flow diagram; collecting data; allocations – linking data with the selected functional block; construction of an inventory table which contains the overall energy and material balance of all inputs and outputs during the entire life cycle of the object under study.

The life cycle description is best to start with the finished product itself, and then develop all the stages of the LC product before and after it. The next step is to determine what proportion of total emissions and material consumption should be attributed to each specific product. The main problem with allocation is the distribution of emissions and material consumption among several products or processes.

The inventory table is the basis for the next step of the LCA – impact assessment. The inventory table data should be processed to achieve a higher level of aggregation, the first step to achieving this is their classification.

The 3rd stage of the study begins with the classification – environmental impact assessment of the WT life cycle.

Classification. A typical source of uncertainty here is the lack of a generally accepted official list of categories of environmental impacts. However, as a result of numerous already performed LCAs, there are "standard" lists of impacts that are appropriate to use. Most often used: resource depletion; global warming; destruction of the ozone layer; toxicity to humans; ecotoxicity; photochemical oxidation; land use; acidification; eutrophication; others (in particular solid waste, heavy metals, carcinogens, radiation, species extinction, noise). The end result of the characterisation is a list of potential environmental impacts and a relative assessment of the contribution of each undesirable impact to each environmental problem, which is called the ecological profile.

Normalisation. Since the results at the characterisation stage cannot be compared, because they are usually presented in different units (CO_2 eq., SO_2 eq., CFC-11 eq.), the following procedure is performed to eliminate this drawback and compare the estimates of ecological profile effects. The normalised effect estimate is the percentage of the annual contribution of a particular product to this effect in a given area.

Weighting, or the determination of significance, is the most difficult and controversial step of assessment, since, as a rule, it is based on subjective reasoning. To compare the effects, weighting coefficients are used, which determine: by the decision of a group of experts – the methods of Eco-indicator'99 and ReCiPe; ecological scarcity Ecological Scarcity methods; monetary damage assessment – EPS 2000 method.

Weighting is performed by multiplying the values of the normalised ecological profile by the weighting coefficients assigned to the category.

Defining ecological indicators of the WT life cycle. The eco-indicator approach distinguishes three categories of damage, the so-called end points: human health, ecosystem quality and resources. Thus, the health of any person who is a member of the present or future generation can be affected by temporary or permanent disability or can lead to premature death. Typically, these types of injury are caused by emissions from production systems. However, this list is far from being complete. For example, harm to health from heavy metal emissions such as Cd and Pb, endocrine disruptors, and harm to health from allergenic substances, noise and odour have not yet been modelled in Eco-indicator'99.

Impact on human health is expressed as the number of lost years of life and the number of years of living with disabilities (Disability Adjusted Life Years – DALY).

Diversity of species is used here as an indicator of the quality of ecosystems. The harm to the ecosystem can be expressed as a percentage of species that are threatened with extinction or which disappear from a certain area within a certain time. For ecotoxicity, Eco-indicator'99 uses the method developed for the Dutch environmental forecast [van de Meent *et al.* 2006]. According to the method, the potentially affected fraction (PAF) of species is determined in relation to the concentration of toxic substances. PAF is determined based on toxicity data for terrestrial and aquatic organisms, such as microorganisms, plants, worms, algae, amphibians, mollusks, crustaceans, and fish.

The study of the wind farm impact on environmental components was carried out taking into account a number of technical characteristics of the WT, which is the main equipment of the project. According to the customer's intentions and the design solution, the designed wind farm consists of separate sites and structures and equipment located on them. Taking into account the wind and weather conditions in the area of the planned activities, as well as noise, vibration and other characteristics, the customer chose the WT of the company Siemens SWT DD-142. The wind turbines are certified according to ISO 9001 and IES 61400-12-1.

The stationary facilities of the wind power station include: the WT operation control system and structures, repair and maintenance facilities and distribution points with power equipment and utilities system, the foundations of towers, WT towers, supports, overhead and underground lines, access roads, other auxiliary structures and service lines necessary for the operation and life of the entire wind farm.

When staging the WT, the availability of roads for transporting equipment and the possibility of organising vehicle access to the WT are taken into account, in particular, the maximum use of the existing infrastructure to minimise environmental impact. The positioning of the WT takes into account the dominant wind directions. The distances between the turbines were determined based primarily on the results of the analysis of the wind characteristics of the territory and considerations for optimising the location of the WT to reduce

[1] The method has been given the name ReCiPe as it provides a "recipe" to calculate life cycle impact category indicators. The acronym also represents the initials of the institutes that were the main contributors to this project and the major collaborators in its design: RIVM and Radboud University, CML, and PRé Consultants.

the impact on the environment, as well as taking into account the visual impact on the population of nearby settlements, tourists, and so on.

The WT location areas provide for temporary construction sites for the installation and maintenance of the facilities. Another category is land plots that are temporarily used for storing structural parts. Along the WT rows, underground cable and service lines and technological roads are designed, which is reflected in the utilities network diagrams.

The boundaries of the WT research system are: production of materials and equipment necessary for the manufacture of WT components and auxiliary structures and foundations (concrete, aluminum, steel, fiberglass, etc.); operation of the existing roads for transportation of WT components and other equipment by specialised trucks from the place of their production to the place of installation; installation of WT by means of cranes; temporarily used land plot of 1.25 ha for storage of structural parts; visual impact of WTs up to 150 m high (taking into account the rotation of the blades); flickering shadow, noise and vibration from the rotation of the blades and the operation of generators; electromagnetic radiation of the designed overhead and cable electric transmission lines and transformer substations; impact on the aquatic environment.

RESULTS AND DISCUSSION

Based on the results of implementing **the 1st stage**, the aim and subject of the study were defined. The aim is to calculate integrated indicators of the WT influence during its life cycle on CLS compartments. The obtained indicators – the subject of the study – will be used to model the impact on the subsystems and layers of the CLS compartments.

According to the LCA procedure, the defined aim and subject of the study allow passing on to the **2nd stage** of the study – a description of the life cycle of WT and the inventory step. Most of the data used comes from the Vestas report [SINHA *et al.* 2016], and from the "Siemens SWT DD-142" datasheet [Vestas 2004]. The establishment of WT can be represented as the fabrication of its three main parts: tower, rotor and nacelle, covering the period from receipt of raw materials to the completion of installation work.

Since data on the consumption of energy used for each production process are not available, the total energy consumption was determined for the entire manufacture of WT and is 7,405 $MW \cdot y^{-1}$ of electricity [Vestas 2005].

The paper takes into account several possible scenarios for waste management. In particular, for the type of waste: steel and ferrous metals – according to the database of Processes of the Ecoinvent system, 90% of steel and iron are recycled; according to the database of Processes of the ETH-ESU 96 system, 10% of steel inactive in landfill conditions is stored on the ground [SINHA *et al.* 2016]; for the type of waste: copper – according to Ecoinvent, 90% of copper is recycled; according to the database of Processes of ETH-ESU 96 system, the remaining 10% of copper inactive in landfill conditions is stored on the ground [CHAPMAN, ROBERTS 1983]. Energy consumption for copper production is 130.3 $GJ \cdot Mg^{-1}$ [UN 1992], and its processing costs are 20% of production, 20% for preservation); for the type of waste: concrete – according to the database of Processes of the ETH-ESU 96 system, 100% of concrete, inactive in landfill conditions, is stored on the ground; for the type of waste: plastics – 100% of plastics and fiberglass is burned [SINHA *et al.* 2016]. According to the database of Processes of the Ecoinvent system, polyethylene terephthalate disposal requires 0.2% of water during incineration in municipal furnaces; during transportation, it is assumed that the recycling site, soil storage and incinerator are located on average 200 km from the WT installation site. Then, for every megagram of processed material, there are 200 km of transportation by a truck with a carrying capacity of 28 Mg.

The inventory was performed in accordance with the defined boundaries, life cycle description and data entered into the program. Its results are presented in Table 1.

Table 1. Inventory table for establishing one wind turbine

Component	Sub-component	Material	Quantity
Rotor	blades	glass-reinforced plastics	$53 \cdot 10^3$ kg
	hub w/nose cone	cast iron	$35 \cdot 10^3$ kg
		low-alloy steel	$21 \cdot 10^3$ kg
		glass-reinforced plastics	$1.4 \cdot 10^3$ kg
Nacelle	generator	copper	$10 \cdot 10^3$ kg
		electrical steel	$23 \cdot 10^3$ kg
	gearbox	cast iron	$42 \cdot 10^3$ kg
		high-alloy steel	$42 \cdot 10^3$ kg
	housing	glass-reinforced plastics	$10 \cdot 10^3$ kg
	main frame	cast iron	$35 \cdot 10^3$ kg
		low-alloy steel	$19 \cdot 10^3$ kg
	main shaft	high-alloy steel	$27 \cdot 10^3$ kg
		low-alloy steel	$4.8 \cdot 10^3$ kg
	transformer	copper	$7.8 \cdot 10^3$ kg
		electrical steel	$18 \cdot 10^3$ kg
Tower	tubular steel	low-alloy steel	$350 \cdot 10^3$ kg
	tower internals	aluminum	$2.6 \cdot 10^3$ kg
		copper	$1.3 \cdot 10^3$ kg
Foundation	ballast	gravel	$5200 \cdot 10^3$ kg
	concrete	concrete	1300 m^3
	reinforcement	reinforcement steel	$560 \cdot 10^3$ kg

Source: own study.

Based on the conducted inventory, in accordance with identified boundaries and entered data presented in Table 1, SimaPro generates a process tree to identify potential impacts. The calculation is performed for each element of the WT LC. Analyzing the diagram, it was found that energy consumption (especially from coal), expressed according to B250 as Electricity of Ukraine, has a significant impact on the environment (57.5%). This can be explained by the influence of fuel consumption and, consequently, resource extraction, as well as increased emissions (greenhouse gases, respiratory inorganic substances, etc.) or the production of carcinogens. As mentioned earlier, this energy is used for such necessary processes as the manufacture of various parts of wind turbines or transportation.

Other stages of the process that significantly affect the result is the production of copper and reinforcing steel with an impact of 13.8% and 11.5%, respectively, as well as the operation and maintenance processes with an 11% impact on the overall result. Data from studies of the content of petroleum products in soil samples selected and analyzed according to the methods described above are presented in (Tab. 1).

The first step to achieving a higher level of data aggregation is their classification. **The 3rd stage** of the study begins with the classification – environmental impact assessment of the WT life cycle.

Classification. The input and output flows of WT life cycle are grouped in such a way that each of the groups represents a selected impact category. Similarly is organised the inventory table in order to qualitatively and quantitatively take into account all relevant emissions or consumption of materials for each category of impact.

A "standard" list of environmental impacts was used (Fig. 1). There are many other impact categories that can be important in certain situations, especially on a local scale. For example, residual solid waste deposits, noise, odour, and landscape degradation. And, although the choice of impact categories is subjective, it has been adjusted to adequately reflect the environmental impact caused by WT.

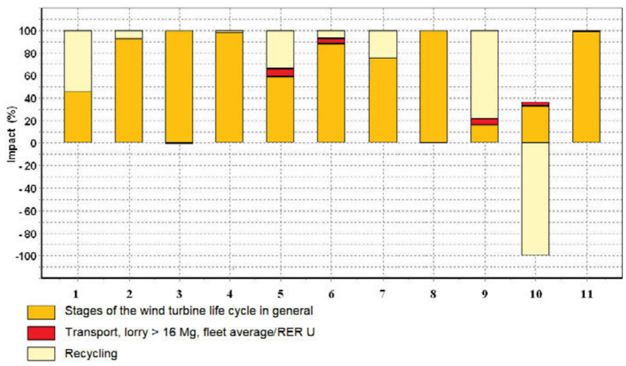

Fig. 1. Characterisation of the wind farm impacts according to the Eco-indicator'99 method: 1 = carcinogenic effects, 2 = effects of respiratory inorganics, 3 = effects of respiratory organics, 4 = climate change – global warming, 5 = radiation effects, 6 = holes in the ozone layer, 7 = ecotoxicity, 8 = acidification and eutrophication, 9 = land use, 10 = mineral depletion, 11 = fossil fuels depletion; source: own study

The production of reinforcing steel is another most important factor which, however, is less significant when compared to electricity generation from coal. Recycling steel and cast iron from a wind turbine has a positive effect on climate change as it replaces the energy required to produce 334 Mg of iron.

The impact of using a wind generator is 2.14 DALY. However, the implementation of the waste scenario (0.883 DALY) reduces this value to an overall impact of 1.25 DALY. Electricity from coal is most conducive to carcinogenic effects due to the production of steel and copper. Since all steel and iron are recycled, the reduction in the amount of carcinogens due to their recycling is greater (0.41 DALY) than in the production of reinforcing steel (0.38 DALY).

The main substances that have a carcinogenic effect and enter the water as ions are arsenic (0.81 DALY) and unidentified metals (0.028 DALY), and those in the air – unidentified metals (0.342 DALY), cadmium (0.06 DALY) and arsenic (0.27 DALY).

Coal for power plants is the largest source of respiratory inorganic. Concrete for WT foundations also has a serious effect on the respiratory system. Dust, nitrogen dioxide and sulphur dioxide (2.33, 1.65 and 1.51 DALY, respectively) are major respiratory threats. The use of the waste scenario makes it possible to reduce emissions of inorganic substances by 15.4% and achieve their total impact of 5.91 DALY.

Fossil fuels, such as coal, oil and gas, are mainly used to generate electricity. The production of metals such as steel or iron is very energy-consuming. Therefore, the production of reinforcing steel is the third largest consumer of fossil fuels. Transportation of raw materials and WT components, as well as its construction, will require a significant amount of diesel fuel, which is expressed as crude oil in Figure 1.

Respiratory organics. The waste scenario in this case is inappropriate, since it itself has a negative environmental impact with a volume of 5.93%. The total emissions are 33.2E–4, among which the main ones are non-methane volatile organic compounds (25.2E–4), as well as methane and unidentified aromatic hydrocarbons (7.45E–4).

The reduction in radiation using the waste scenario is 16.5% with a total impact of WT amounting to 3.79E–3. Radiation is mainly caused by radon-222 and carbon-14 in the air. Their radiation is 2.55–3 and 1.22–3, respectively.

The ozone layer. This is another category where the waste scenario has a negative impact which is 7.34% of the total impact, or 5.27E–4. The main cause is bromotrifluoromethane, also known as gallon 1303 with an effect of 5.02E–4.

Ecotoxicity. This is the second largest category with a positive effect of the waste scenario, which reduces the environmental impact by 47.8%. After that, the total impact is 2.32E+62.32E6 PAF·m^{-2}·y^{-1}, with the largest contributions from unidentified metals (1.25E+6), nickel and zinc (6.33E+5 combined) and lead (9.64E+4) that are in the air.

Acidification/eutrophication. Here, the implementation of the waste scenario gives a slight decrease in the negative impact by 4.07%, which in total amounts to 1.38E+5 PAF·m^{-2}·y^{-1}. The largest contribution to this value is made by nitrogen oxides and sulfur oxides containing 1.06E+5 and 2.88E+4, respectively.

Land use. The waste scenario in this case is very appropriate as it minimises the negative impact by 32.3% and the overall impact is 3.1E+4 PDF·m^{-2}·y^{-1}. This is mainly recycling (9.18E+3) or occupancy of industrial zones (1.3E+4). Due to the waste scenario, landfill occupancy is reduced by 1.46E+4, which most significantly reduces the impact.

Mineral deposits. The waste scenario is at its maximum here, which reduces the negative impact by 79.1% and amounts to 1.01E5 MJ of the surplus as a whole. The negative impact is mainly exerted by two minerals: nickel (1.98% in silicates, 1.04% in raw ore) and copper (0.99% in sulphide, 0.36% in pure copper and 8.2E–3% in raw ore). They amount to 6.47E+4 and 3.68E+4 MJ, respectively.

As can be seen, the waste scenario has a different impact on each category, among which there are three, where its impact is most significant: minerals, ecotoxicity and carcinogenic effects. This is due to the fact that about 80% of waste (except for concrete) can be recycled and reused, mainly copper, iron and aluminum, and, obviously, this will reduce their extraction, and limit the release of elements such as cadmium, nickel, lead or arsenic that accompany production.

Normalisation. Figure 2 shows the normalised environmental pressures for the impact categories that were selected for analysis, where there are two categories that are most significant for both the overall impact and the waste scenario.

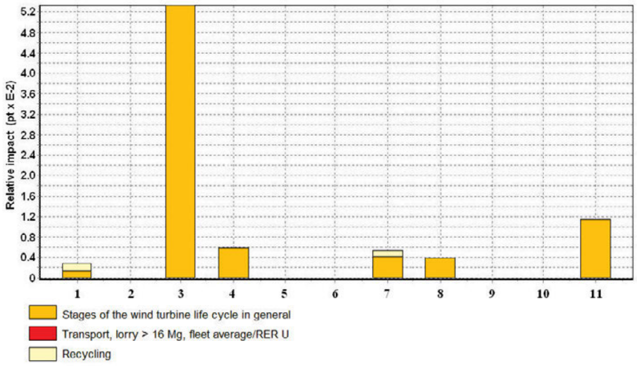

Fig. 2. Normalised life cycle impact assessment for a wind farm; 1–11 = as in Fig. 1; source: own study

In particular, the normalised ecological profile (Fig. 2) shows that respiratory inorganics account for 0.052 pt of all CO_2 equivalents in the WT life cycle. Thus, WT life cycle has a stronger impact on global warming than on the ozone layer depletion and has almost no effect on the flora in the region where a WT is built and operated. The main difficulty at the stage of normalisation is the lack of appropriate values that represent the annual contribution to environmental problems.

Respiratory inorganic substances, such as oxides of nitrogen, sulfur and many others, have the strongest impact on the environment with a total of 454 pt. They are emitted mainly during fuel combustion. However, it should be noted that the waste scenario is the most important for this particular category. Even though the impact of minerals has decreased by almost 80% and inorganic – only by 15%, the end result shows that this latter amount is larger.

The next strongest impact on the environment is fossil fuels – 365 points. This is mainly due to the use of electricity throughout the entire process; this electricity is usually produced from coal, oil and gas. The contribution of alternative resources (hydro- and nuclear power plants) is insignificant. It is obvious that consumption occurs at a very early stage of the process, but affects the subsequent ones, where consumption is the highest – the manufacture of turbine parts and its transportation.

Climate change also has a significant impact. It is caused by global warming produced by greenhouse gases such as carbon dioxide or methane, and can lead to changes in sea level, rainfall distribution, or an increase in the intensity of weather disastrous events such as hurricanes.

Normalisation confirms the choice of climate change, carcinogens, respiratory inorganic and fossil fuels as the main categories of characteristics. They have significantly stronger impact than the rest of the categories.

Weighting – determining importance. According to the Eco-Indicator'99, it is assumed that impacts on health and the ecosystem are twice as important as impacts on resources; respectively, the weighting factors are 40, 40, and 20%. This option was chosen for practical reasons. Although the choice itself is not so important if the levels of damage are well comparable. For example, if all target values are doubled, all weights will be halved. Obviously, this will not affect their mutual correlation. The weighting itself is performed by multiplying the values of the normalised ecological profile by weighting factors assigned to the category.

Determining the ecological indicators of wind farm LC. In the next two steps, the exposure and exposure effects of loads are calculated using European average data. The Eco-indicator approach identifies three categories of damage: human health, ecosystem quality and resources (Fig. 3). The first category includes: carcinogens, respiratory substances, climate change, radiation, the ozone layer destruction, and ecotoxicity. Ecosystem quality includes acidification/eutrophication and land use. The third category – natural resources – contains minerals and fossil fuels.

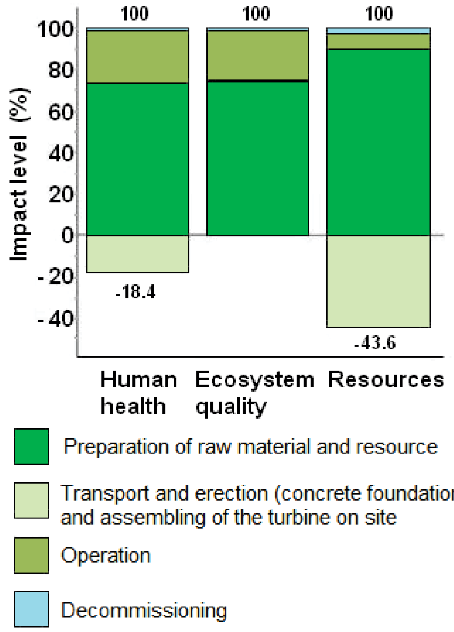

Fig. 3. Assessment of the wind turbine impact by three combined categories for stage of the life cycle; source: own study

Eco-indicator values for a given impact are expressed as the sum of the impacts for each of the three categories. Each category of impact is expressed by one unit. Impact on human health is expressed as the number of lost years of life and the number of years of living with disabilities – DALY. The impact on ecosystem quality is expressed as the loss of species in a certain area over a certain period of time PDF $m^{-2} \cdot y^{-1}$. Resource depletion is the excess energy required for the subsequent extraction of minerals and fossil fuels. Table 2 shows the weights obtained in the study for three categories of damage: resources, ecosystem quality and human health, according to Eco-indicator'99.

The 4th stage of the study – interpretation of the results. According to the ISO 14040 and ISO 14044 standards, the interpretation covers three types of procedures: uncertainty analysis, analysis of results sensitivity to changes in assumptions and parameters (sensitivity analysis), and analysis of the contribution of individual processes/substances to the overall impact (contribution analysis).

Table 2. Weighting coefficients according to Eco-indicator'99

Substance/Type of land use	Damage category	Hierarchical weights	Egalitarian weights	Individualist weights
Resource use				
Coal (29.3 MJ·kg^{-1})	resources	0.00599	0.0687	0
Crude oil (41 MJ·kg^{-1})	resources	0.140	0.114	0
Natural gas (30.3 MJ·kg^{-1})	resources	0.108	0.0909	0
Aluminum ore	resources	0.0119	0.0168	0.667
Copper ore	resources	0.00987	0.0140	0.553
Iron ore	resources	0.000690	0.000976	0.0387
Zinc ore	resources	0.00178	0.00253	0.10
Ecosystem quality land use				
Industrial area	occupancy	0.0655	0.0819	0.0466
	conversion	1.96	2.45	1.39
Forest land	occupancy	0.00858	0.0107	0.00610
	conversion	2.68	3.35	1.91
Emission to air				
CO	human health, respiratory	0	0.00579	0
CO_2	human health, climate	0.0297	0.0222	0.0497
NH_3	human health, respiratory	0.0902	0.673	0.938
NH_3	ecosystem quality	1.21	1.52	0.863
NH_3	sum, NH_3 to air	2.112	2.193	1.801

Source: own study.

One of the sources of uncertainty may be inaccuracies in data measurement, which, in particular, are eliminated by Monte Carlo methods. Another source of uncertainty is the correctness of the models adopted for analysis. The reasons for this may be the allocation of impacts, methods of waste management, especially in the distant future, functional units adopted for comparison, and so on.

Sensitivity analysis reveals the influence of the most important assumptions on the assessment results. It is performed by means of analysis "if". In cases when the results of the LCA are critically dependent on changes in assumptions, these assumptions and considerations regarding their correctness should be clearly stated.

Contribution analysis. In many cases, the ecological profile of the product is formed by 5% or even 1% of all processes involved in the life cycle. In other words, usually only a certain number of processes play a decisive role in the ecological profile of a product, while all others can be neglected without seriously affecting the results. The contribution analysis is aimed at identifying the processes of the highest importance and determining their contribution to the environmental index. This information allows you to greatly simplify the process tree and focus on its most important components.

Thus, the analysis of the contribution of individual processes/substances to the overall impact reveals the significance of their impact on the overall results. It often turns out that of hundreds of analysed elementary processes, the influence of only a few is significant, the analysis of which should be focused on.

CONCLUSIONS

A concept is proposed for assessing the environmental impact of alternative energy sources, which are wind turbines (WTs) during their life cycle (LC); this concept will allow identifying the existing and future states of complex landscape systems (CLSs) based on environmental simulation of the impact of WT on CLS compartments. Using the SimaPro software and the Eco-indicator'99 methodology, an integrated system of indicators of the impact of a wind power plant on the layers and subsystems of the CLS compartments was obtained. A process tree diagram is constructed for identification of potential impacts, their characterisation, weighting and ranking. Analysing the diagram, it was found that the consumption of energy from thermal electric power station has the strongest impact on the environment – 57.5%; also significant are the impacts of the production of copper and reinforcing steel with the corresponding values of 13.8% and 11.5%, as well as the processes of operation and maintenance of WT with an effect of 11% of the overall result.

The results of the assessment of indicators, expressed in eco-points, were obtained, which shows that the most significant reduction in harmful environmental impact can be achieved during the following WT life cycle stage – dismantling and disposal, in particular, using the developed scenarios of waste management. In general, the strongest adverse environmental impact with an eco-indicator value of 14.1 occurs during the WT manufacturing stage. Especially it is related to the type of electricity used. The analysis showed that although most of the products were recycled, and minerals could be used again, fossil fuels still have the most impact on the resource, and this issue should be taken into account when improving the system. Energy consumption for WT manufacturing is the largest influencing factor in various categories of characteristics. Similar results are demonstrated by assessment of the impact of WT life cycle in three combined categories: impact on human health, impact on ecosystem quality, and resource depletion. The most significant impact on these categories occurs precisely at the manufacturing stage. It is worth exploring the possibilities for improving the energy efficiency of the WT manufacturing process to reduce its harmful environmental impact, in particular CO_2 emissions.

It should be noted that WT also has a visually negative impact on the environment. However, due to its completely subjective nature, the category was not taken into account. It is obvious that wind energy is competitive compared to generating energy by burning gas, coal or oil, although hydropower has turned out to be more environmentally friendly. However, the difference is insignificant, and both of these sources should undoubtedly be considered as a step towards sustainable development.

Regarding the layers and subsystems of the CLS compartments, the most significant consequences usually occur at the stage of transportation, installation and assembly of the WT, as well as the removal of individual components or the entire turbine at the end of its operation. This impact is local and temporary; however, given the significant amount of damage to the ecosystem, possible approaches should be identified and measures to reduce it should be worked out.

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