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Computer Simulation of the Influence of Wind Power Plants on The Compartments of The Complex Landscape System by The Method of Life Cycle Assessment

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Abstract–It is proposed to apply the concept of life cycle assessment of alternative energy sources, such as wind turbines, to assess their environmental impact. By means of simulation modeling, using SimaPro software, obtained was an integrated system of indicators of the impact of wind energy systems on the layers of subsystems of the compartments of complex landscape systems (CLS). A process tree has been built to identify potential impacts, as well as to characterize, weigh and rank them. Based on the assessment analysis of various environmental impacts, it was determined that significant consequences for the layers of the subsystems of the CLS compartments usually arise at the stage of transportation, installation and erection of wind turbines, as well as the removal of individual components or the entire turbine at the end of its operation. It is shown that the study all the processes alone, starting from the formation and ending with the utilization of landscape-technogenic systems will reveal the possible integrated effects of their impact on the environment.

Keywords-environment; environmental impact; life cycle assessment; wind power plant; wind farm

I. Intruction

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” 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 life cycle, 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 modeling the assessment of ecosystem conditions, which has become the subject of this study.

II. Literature Data Analysis and Problem Formulation

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 [1].

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 [2].

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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 [3 & 4].

The problems of modeling environmental processes and systems at various levels have been investigated by many domestic and foreign scientists. A special contribution to this area was made by: I.S. Blagun, V.V. Vitlinsky, A.K. Prykarpatsky, V.M. Geyts, M.V. Odrekhivsky, M.I. Skrypnychenko, B.V. Gnedenko, I.M. Kovalenko, A.V. Yatsyk, A.B. Kachynsky, V.I. Muntiyan. 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 [5-7] 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 B. Cleary et al. [8], E. Martinez et al. [9], Ch Ghenai [10], T. Toth et al. [11], and in the work of Russian scientists B.V. Ermolenko et al. [12], as well as one of the largest manufacturers of wind turbines – the Danish company Vestas [20.Not many current life cycle assessment studies exist for wind turbines with high rated power (600 kW). The available studies [14–21] 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.

III. Purpose, Object and Subject of the Studies

A. *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.

B. *The Object of the Study*

were 34 wind turbines 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 Polonyny of the Eastern flysch Carpathians.

C. *The Subject of the Study*

is CLS in which wind turbines operate. CLS is a biological system characterized 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 organization and a large number of different layers, between which there are close material, energy, and hierarchical connections. The Borzhava Polonyny of the Eastern flysch Carpathians, by definition [22 & 23], are 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 characterized 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 analyzed using SimaPro software which is a professional tool for collecting, analyzing, and monitoring the environmental characteristics of products and services. With its help, it is possible to model and analyze complex LCs in a systematic and understandable way.

In particular, SimaPro makes it possible to analyze products taking into account waste management scenarios which can be modeled 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 analyze 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 raw materials for the production of wind turbine 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 wind turbine 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.

IV. Methods of the Study

The other term, crucial to understanding the holistic approach of the life cycle, is the life cycle assessment. It encompasses all the processes required to fulfil the function provided by a product or service (Figure 1), [24]. At present LCA is used for the following fields of application [25]: infrastructure; process industry; energy production; transportation; heavy industry; consumer goods; livelihood.

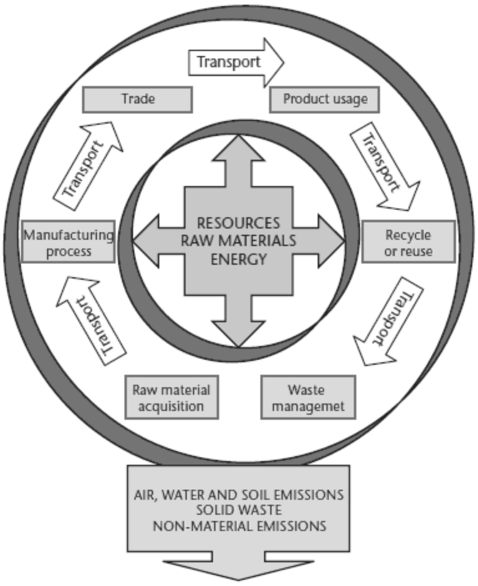

Figure 1. Product life cycle [23]

The ISO 14040/44 standard defines the concept of life cycle assessment (LCA) as a compilation of inputs and outputs of a production system and their potential environmental impact at all stages of a life cycle – from raw materials extraction and energy production to decommissioning. Therefore, LCA is a combination of the comprehensive environmental characteristics of a product / service / process, where a quantitative measurement of their environmental friendliness is the result of the LCA process [26].

Thus, LCA is a technique for assessing potential environmental aspects and potential aspects associated with a particular product by using: compiling a list of important flow balances; assessing the potential environmental impacts of these flows; interpretation of the results of the previous stages of analysis in terms of the study objectives, etc.

The LCA procedure is governed by the standards: ISO 14040: Principles and Framework, and ISO 14044: Requirements and Guidelines. However, the use of standards does not exclude the subjectivity of assessments in determining the boundaries of analysis (the boundaries of the system), the level of importance of impacts, and the comparison of the strength of impacts of various nature. Therefore, adherence to standards and the use of software products does not guarantee the objectivity of results; therefore, their use for public information requires accurate documentation and independent expert evaluation. The use of the Product Category Rules (PCR), which are regulated by the ISO 14025 standard, more strictly regulates the LCA procedure and provides greater objectivity to the ratings and Environmental Product Declarations (EPD). The preparation of Environmental Product Declarations is an essential application of LCA. In some countries, the practice of their application is very common.

At the European level, LCA standards are refined and supplemented by the ILCD Handbook (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 [27]. 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.

In addition to multifaceted assessments of LC that give a comprehensive characterization of the impact, the analysis also uses estimates focused on a particular impact, say, carbon footprint (GHG Protocol and ISO 14067) or hydrogen footprint (ISO 14046).

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 (LCI) – the formation of a life cycle model (LC), all environmental inputs and outputs being displayed.

Stage 3. Life Cycle Impact Assessment (LCIA) is a study of the importance of all inputs and outputs in terms of their potential impact. ISO 14040/44 distinguishes the following steps in impact assessment:

- mandatory stages: classification and characterization ;
- additional stages: normalization, ranking, grouping, and weighting.

Stage 4. Interpretation of the results obtained [26]. 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 Sbeq); abiotic depletion – fossil resources (ADP-fossil, MJ net caloric value); acidification (AP, kg SO_2eq); eutrophication (EP, kg $(PO_4)_3$–eq); global warming (GWP, kg CO_2eq); ozone layer depletion (ODP, kg CFC-11eq); formation of a photochemical ozone layer (POCP, kg C_2H_4eq) [28].

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-points, Eco-indicator, EPS system, MIPS concept, etc. [29]. 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.) [26].

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 recognized and well-grounded for the analysis of such area.

The stages of the study include the following steps: determining the background of the problem, functional unit description, building a block diagram of the LC, determining the boundaries of the system, Waste scenario, inventory, generating the process tree, classification, characterization, normalization, comparing impacts, determining the environmental index.

A. Background of the Problem

Due to more environmental concerns and more environmental restrictions, renewable energies are developing fast these days. Wind power is the most-cost-effective renewable energy technology producing electricity (except large hydropower) and the fastest growing market with a growth of an average cumulative rate of 28 % over the past five years [30]. And this tendency will continue the next years. By the end of 2004, the capacity of wind energy installed globally had reached a level of almost 48.000 MW. Europe accounts for 72 % of the total installed capacity (34.205 MW) and for 73 % of the annual market growth during 2004 (5,800 MW).

But is this renewable energy technology as “green” (environmentally friendly) as it is always claimed? The argument behind is usually based on the environmental effects of the operation phase of the wind turbine (that will produce electricity with no consumption of fossil fuel and no pollution) excluding the whole manufacturing phase (from the extraction to the erection of the turbine including the production processes and all the transportation needs) and the decommission phase.

B. Functional Unit

The function of the wind turbine is to produce electricity. MWh as a common measure of electricity should be used as the functional unit. However, due to limited time, we chose the electric power that one unit of wind turbine generates during its life span as functional unit in this study for simplicity. 1 wind turbine of the specified manufacturer [31] produces 7,890 MWh/year, corresponding to a capacity factor (the amount of energy a facility generates in one year divided by the total amount it could generate if it ran at full capacity [32]) of 30.02 %, which means 157,800 MWh electricity generated in its life span of 25 years. The figure may vary in different sites due to various wind conditions. Therefore, the functional unit in this study is 157,800 MWh of electricity.

C. Process Flowchart

Figure 2 describes the life cycle of the wind turbine from manufacture to waste management. Transmission stage of the energy produced by the wind turbine is not included, since it is considered that the transmission of electricity from any energy source would be the same. Emissions are represented as “Em”.

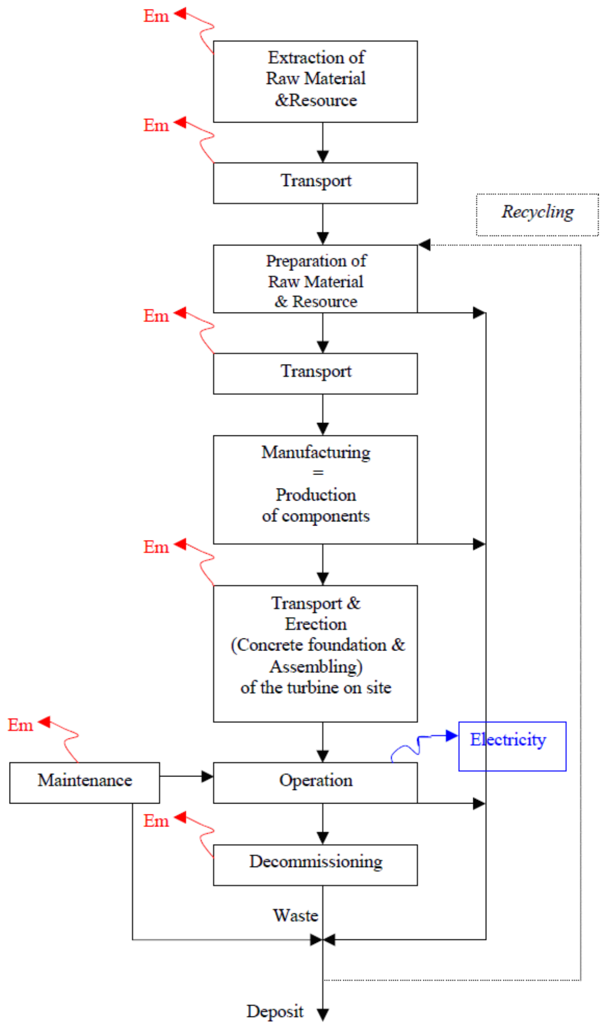

Figure 2. Flowchart of wind turbine life

D. Boundaries of the system

Another important task at the first stage of the LCA is to determine the boundaries of the system under study, as it is important to discard influences that are not essential for the analysis. While the boundaries of the system being defined, the phenomenon of recursion occurs: the extraction of raw materials or energy production requires basic work equipment (machinery, transport, etc.), and they also have their own life cycle (endless regression). The exclusion of individual components of the system from consideration may significantly affect the results of the assessment.

Therefore, in order to avoid mistakes, the LCA practices use two approaches: basic work equipment is not considered at all in the analysis or only the effects of raw material extraction and transportation are taken into account. Databases such as Ecoinvent and USA Input Output account for the basic work equipment using the second approach. In the LCA of natural systems, these systems are viewed as economic rather than natural. Therefore, carbon sequestration and land use impacts are not considered at all, but environmental pollution by pesticides is taken into account.The ReCiPe method, which is implemented in SimaPro, is based on this principle of determining the boundaries between natural and economic systems.

The first stage is completed by determining the the goal and scope of the study. The next stage of the study, according to the LCA procedure, is a description of the life cycle (*Life Cycle Inventory).* The following data are required to identify and describe the effects of the LC: information about the object under study to be collected by the analyst (Foreground data) and background data on physical / chemical dependencies and processes (Background data) contained in the literature and Ecoinvent v3 database which is offered together with the SimaPro program.

Most of the data used in our model comes from an LCA report realized by Vestas [31] and from the General Specification of the "Siemens SWT DD-142" [33]. Fig.3 shows, as an example, the model generated by SimaPro program for the turbine under study, which will be discussed further in the "Results" section.

The manufacture of the turbine covers the period from obtaining the raw materials to the completion of the wind turbine. The manufacture of the turbine can be decomposed of the manufacture of the three main parts of the turbine: the tower, the rotor and the nacelle.

However, as the data for the energy consumption used for each manufacture process were not available, the total energy consumption has been defined for the whole turbine manufacture and operation and represents 7405 MWh electricity. The total energy consumption during the production phase is 7795 MWh [34]. But this figure includes not only the energy needed for the turbine manufacturing and operation but as well the energy needed for the whole processing phase of the raw material. So we have subtracted 390 MWh (figure that was calculated with the data available in SimaPro) from 7795 MWh to ensure the energy consumption in the raw material is not double counted. Electricity Denmark B250 (which is a mix-production of the average electricity produced in Denmark) from the data base BUWAL250 has been used in SimaPro.

The tower is made of plates of steel and it has been assumed that the tower is made of 100 % steel [31]. Reinforcing steel, at plant / RER S from the data base Ecoinvent system process has been used in SimaPro. To manufacture the 105 meters height tower of our turbine considered, 275 tons of steel are needed [33. The painting of the tower has not been taken into consideration in our model.

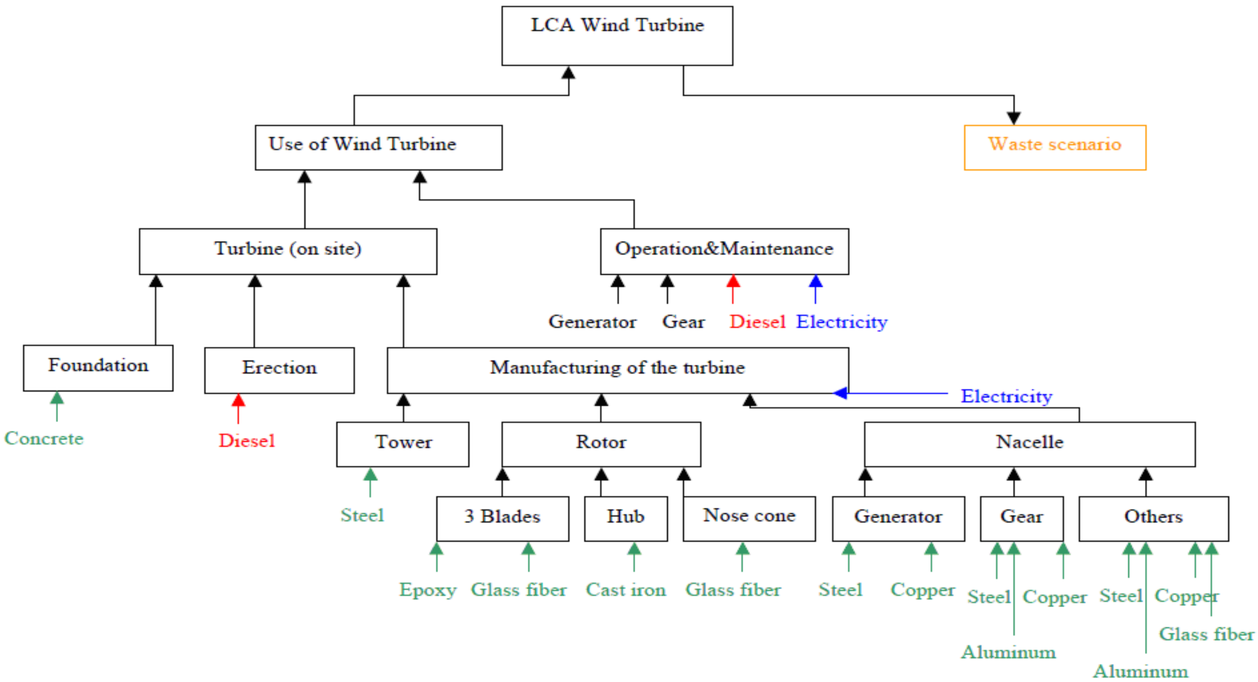

Figure 3. Model for wind turbine in SimaP

The rotor is composed of 3 blades, the hub and the nose cone. The blade of the Vestas turbine is made of Prepreg that is one kind of glass fibre impregnated with epoxy resin. Prepreg is assumed to be composed of 60 % of glass fibre and 40 % of epoxy [31]. Epoxy resin I from the data base IDEMAT 2001, and Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER S from the data base Ecoinvent system process have been used in SimaPro. A blade weight is 6.6 tons but as 10 % of the Prepreg turns into waste due to cut-offs, 7.3 tons of Prepreg is needed for the manufacturing of one blade (2.9 tons epoxy and 4.35 tons glass fibre) [31 & 33]. There is also a few amount of carbon fibre in the composition of the blade but as we could not collect data for it, it has been neglected. And one more time, the painting of the blade has not been taken into consideration in our model.

The hub is made of cast iron and weighs 8.5 tons [33] Cast iron, at plant / RER S from the data base Ecoinvent system process has been used in SimaPro.

The nose cone is the shell that will recover the hub. The total weight of the hub and the nose cone is 20 tons [32], so the nose cone weighs 11.5 tons. It is constructed of fibre glass-reinforced polyester. Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant / RER S from the data base Ecoinvent system process has been used in SimaPro. Again the painting of the nose cone has not been taken into consideration in our model.

The nacelle consists of the nacelle cover, the generator, the gear, the transformer, the yaw system, the electronics. As we will have to change once the generator and the gear during the life-time of the turbine (see the Operation & Maintenance phase), we model the nacelle as composed of three main components: the generator, the gear and frame, machinery and shell (this last unit includes all the nacelle components except the generator and the gear that are treated separately).

The generator weight is given to be 8.5 tons [33]. It is assumed to be composed of 35 % copper and 65 % steel [35]. Copper, primary, at refinery / GLOS from the data base Ecoinvent system process and Reinforcing steel, at plant/RER S from the data base Ecoinvent system process have been used in SimaPro. A generator is made of much more material as copper and steel (that are however the main materials). But as far as no other more detailed data were available, the above rough model has been chosen.

The gear system (called as well gearbox) has a total weight of 23 tons [32]. It is assumed to be composed of 98 % steel, 1 % copper and 1 % aluminum [36]. Reinforcing steel, at plant / RER S from the data base Ecoinvent system process, Copper, primary, at refinery/GLOS from the data base Ecoinvent system process and Aluminum, production mix, at plant/RER S from the data base Ecoinvent system process has been used in SimaPro.

This unit has a given weight of 37 tons [31]. It is assumed to be composed of 85 % steel, 8 % aluminum, 4 % copper and 3 % Glass Reinforced Plastic [36]. Reinforcing steel, at plant/RER S from the data base Ecoinvent system process, Aluminum, production mix, at plant/RER S from the data base Ecoinvent system process, Copper, primary, at refinery / GLOS from the data base Ecoinvent system process and Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER S from the data base Ecoinvent system process have been used in SimaPro. This unit is composed of so many different components (nacelle cover, transformer, electronics, shaft…) that all the data for each component were not available. The above model is based on accounting of the main materials used and their percentage regarding the total weigh of the unit.

Three different phases have to be achieved to obtain as a result an installed turbine in a specific site. First we need a turbine (that is to say that the turbine manufacturing phase has been completed); then some foundation has to be build on the site; and finally the different parts of the turbine (tower, rotor and nacelle) have to be erected and assembled. The foundation is made on site and consists of filling up a hole (typical size 15m × 15m and 2 m deep with some concrete reinforced by steel: the total amount of reinforced concrete is 1200 tons [31]. Concrete (reinforced) I from the data base IDEMAT 2001 has been used in SimaPro. The energy to realize the excavation of the hole has not been considered. This phase includes the transportation of the different parts of the turbine to the site and the erection of these parts (by a crane) in order to build up the turbine on site.

The resource used is therefore mainly fuel (diesel) and the amount of diesel has been calculated to be 5382 kg (as the energy consumption for the Erection&Transportation is given to be 74 MWh, i.e. 266400 MJ [34] and the heating value for diesel is 49.5 MJ / kg). Diesel stock Europ S from the data base ETH-ESU 96 System process has been used in SimaPro.

The phase “Use of wind turbine” includes the phase of operation and maintenance of the wind turbine (onsite). The operation of the turbine requires almost no resource since the turbine uses the energy contained in the wind to produce electricity without emitting any kind of pollutant. Nevertheless some energy is needed for a yaw system operation, which is used for turning the wind turbine rotor against the wind. However, due to the lack of specific data it is included in the total energy consumption and allocated to the manufacture phase.

The energy consumption due to the maintenance is mainly fuel consumption as far as maintenance is mainly transportation of the personnel to the site for regular check up of the turbine.

The amount of diesel has been calculated to be 1020 kg (as the energy consumption for the Erection&Transportation is given to be 14 MWh [34]). Diesel stock Europe S from the data base ETH-ESU 96 System process has been used in SimaPro.

Furthermore the gear and the gearbox are replaced once during the 25 years life-time of the wind turbine. So we have included as “resources” used during the operation and maintenance phase, the gear and the generator (already described before and including the impact of their manufactures).

But as the energy required for their manufacture has been taken into account as a general figure for the manufacture of the whole turbine, 608 MWh of electricity has to be added at this point to make sure that all the resources used for the gear and gearbox manufacture has been properly accounted for (those 608 MWh corresponds to 8.2 % of the electricity use for the whole manufacturing process of the turbine (= 7405 MWh) as the weight of the gear and the generator (31.5 tons) corresponds to 8.2% of the total weight of the turbine (385.5 tons). Electricity Denmark B250 (which is a mix-production of the average electricity produced in Denmark) from the data base BUWAL250 has been used in SimaPro. The change of oil and lubricants (required for all the moving parts like the gear) are included in the global energy consumption expressed in kg Diesel and are not accounted for on their own used resource since it is a small use compared to diesel use.

Waste scenario:

- Steel and cast iron – 90 % of the steel and cast iron is recycled and the remaining 10 % is land filled [31]. Recycling steel and iron/RER S from the data base Ecoinvent system processes (Waste type: Steel; Ferro metals), and Steel (inert) to landfill S from the data base ETH-ESU 96 System processes (Waste type: Steel; Ferro metals) have been used in SimaPro.
- Copper – 90 % of the copper is recycled and the remaining 10 % is land filled [31]. Recycling copper as copper, primary, at refinery/GLO S in the database Ecoinvent system processes. The energy consumption during copper production is 130.3 GJ/ton [37]. Energy consumption for copper recycling is 20 % of production (13 % in Energy & Recycling [38], for conservation, we use 20%). The energy consumption in recycling translated to electricity is 7 MWh Electricity Denmark B250. Copper (inert) to landfill S from the data base

ETH-ESU 96 System processes (Waste type: Coppers) have been used in SimaPro.

- Glass fibre and plastics – 100% of the glass fibre and plastics are incinerated [31]. Disposal, polyethylene terephtalate, 0.2% water, to municipal incineration / CH S from the data base Ecoinvent system processes (Waste type: Plastics) has been used in SimaPro.
- Concrete – 100% of the concrete is land filled. Concrete (inert) to landfill S from the data base ETH-ESU 96 System processes has been used in SimaPro.
- Transportation – It has been assumed that the recycling station, landfilling and incineration plant are situated in average at 200 km away from the site; i.e. for each ton recycled, 200km of transportation are accounted for. Truck 28t B250 from the data base BUWAL 250 has been used in SimaPro.

V. Results of the Studies

Generation of electricity due to wind does not have a significant negative impact on the environment and the social sphere, in addition there is a reduction in emissions of greenhouse gases and other harmful substances into the atmosphere. According to the estimates of the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, only due to the planned commissioning of wind farms with a capacity of 16,000 MW by 2030, the average annual carbon dioxide emissions will not increase by 32 million tons, i.e. annual gas savings will amount to 14.4 billion m^3.

However a wind farm, like any other object of economic activities, causes changes in the natural characteristics of the landscape and the properties of its components, which leads to the formation of man-made geocomplexes [39] on the one hand, and on the other hand, achieves several positive environmental results: it is a source of renewable energy and prevents the depletion of natural non-renewable resources.

The study of the wind farms impacts on environmental components was carried out taking into account a number of their parameters, including technical characteristics. According to the intentions of the Customer and the design solution, the designed wind farm consists of separate sections and placement of facilities and equipment on them. The main equipment of the project is wind turbines. Considering wind and weather conditions in the territory of the planned activities, as well as noise, vibration and other characteristics, the customer selected a wind turbine manufactured by Siemens SWT DD-142. The wind turbines are certified according to ISO 9001 and IEC 61400-12-1.

Stationary wind farm objects include: wind farm operation management system and facilities, repair and maintenance base facilities, distribution points with power equipment and engineering communication utilities, foundations of towers, wind turbine towers, supports and aerial and underground cable lines, access roads, other auxiliary facilities and engineering communications necessary for the operation of the wind farm, as well as ensuring the life support of the staff.

When placing a wind turbine, the following is taken into account: the availability of roads for transporting equipment and the possibility of arranging access to the wind turbines, in particular the maximum use of the existing infrastructure to minimize the environmental impact. The positioning of the wind turbines 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 optimizing the location of the wind turbines to reduce environmental impacts, as well as taking into account the visual impact on the population of the nearest settlements and tourists.

In the territory where the wind turbines are located, it is supposed to temporarily arrange construction sites for installation and maintenance of the facilities. Another category are land plots which are temporarily used to store the parts of the structures.

Along the wind turbine rows, there will be located underground cable and communication lines, and technological roads, which is reflected in the schemes of engineering networks.

A. Boundaries of a Wind Turbine Research System are:

production of materials and equipment necessary for the manufacture of components of the turbine and auxiliary structures, platforms (concrete, aluminum, steel, fiberglass, etc.); the usage of the existing roads for transportation of the wind turbine components and other equipment from the place of their production to the place of installation of the equipment by means of specialized trucks with trailers; installation of the wind turbines using cranes; a land plot of 1.25 hectares temporarily used to store parts of the structures; visual impact of wind turbines with a height of up to 150 m (taking into account the rotation of the blades); shimmering shadow; the noise and vibration generated by the rotation of the blades and the operation of the generators; electromagnetic radiation of the designed aerial and cable power lines and transformer substation; impact on the water bodies.

The results of the first stage made it possible to determinate the goal and scope of the research. The goal of the analysis is to calculate integrated indicators of the impact of wind turbine during its life cycle on the CLS compartments. The scope of the research – the indicators obtained will be used to model the impact on the subsystems and layers of the CLS compartments.

According to the LCA procedure the goal and scope defined in the work, as well as the model generated by the SimaPro program (Fig. 3) made it possible to continue the life cycle description of the wind turbine and move to its inventory.

B. The inventory is Then

completed in accordance with the defined limits and the data presented in Table. 1 The inventory phase is the core of an LCA and is a common feature of any LCA. During this phase all the material flows, the energy flows and all the waste streams released to the environment over the whole life cycle of the system under study are identified and quantified. The final result of the inventory analysis is an inventory table. The inventory phase has four separate sub-stages:

- Constructing a process flow chart (so-called process tree).
- Collecting the data.
- Relating the data to a chosen functional unit (allocation).
- Developing an overall energy and material balance (all inputs and outputs from the entire life cycle) – an inventory table.

TABLE I. SELECTED ITEMS IN THE INVENTORY TABLE FOR THE PRODUCTION OF 1 WIND TURBINE, OBTAINED WITH THE SIMAPRO SOFTWARE

Component	Sub-component	Material	Quantity
Rotor	Blades	Glass-reinforced plastics	53 t
	Hub w/nose cone	Cast iron	35 t
		Low-alloy steel	21 t
		Glass-reinforced plastics	1.4 t
Nacelle	Generator	Copper	10 t
		Electrical steel	23 t
	Gearbox	Cast iron	42 t
		High-alloy steel	42 t
	Housing	Glass-reinforced plastics	10 t
	Main frame	Cast iron	35 t
		Low-alloy steel	19 t
	Main shaft	High-alloy steel	27 t
		Low-alloy steel	4.8 t
	Transformer	Copper	7.8 t
		Electrical steel	18 t
Tower	Tubular steel	Low-alloy steel	350 t
	Tower internals	Aluminum	2.6 t
		Copper	1.3 t
Foundation	Ballast	Gravel	5200 t
	Concrete	Concrete	1300 m^3
	Reinforcement	Reinforcement steel	560 t

To develop a life cycle it is best to start from the product itself and then follow all upstream and downstream life stages. Then we have to determine which part of the total emissions and material consumption should be attributed to each specific product. The same applies to multi-input processes. Petrol production can serve as an example of a multi-output process.

The problem of how to divide emissions and material consumption between several product or processes is called allocation. Several methods have been developed to deal with allocation.

C. Substitution of Allocation

– no allocation in fact. As allocation always require more or less subjective decisions, ISO recommends to avoid allocation if possible. This can be done by extending the system boundaries i.e. by including processes that would be needed to make the same by-product in the conventional way.

According to estimates by the US National Renewable Energy Development Laboratory (NREL), zones of permanent and temporary exposure are distinguished at all stages of the life cycle of wind farms. Zones of permanent exposure make up 1–2% of the total area occupied by wind farms. Temporary exposure zones occupy from 1 to 6% of the territory of the wind farm; at the same time, those sections of wind farm sites that remain outside the influence of the construction can be used for other purposes, for example for growing crops, or for grazing, or recreation. This is an additional gain resulting from the process associated with the analysed product. This fact should be reflected in the main product's environmental profile. Then the environmental load at the stage of production and transportation of wind turbines, which is avoided as a result of other positive factors, can be subtracted from the total environmental load. Thus, it is possible to calculate a part of the emissions and consumption of materials for which the main product is responsible, and the rest can be attributed to the prevention of undesirable environmental impact.

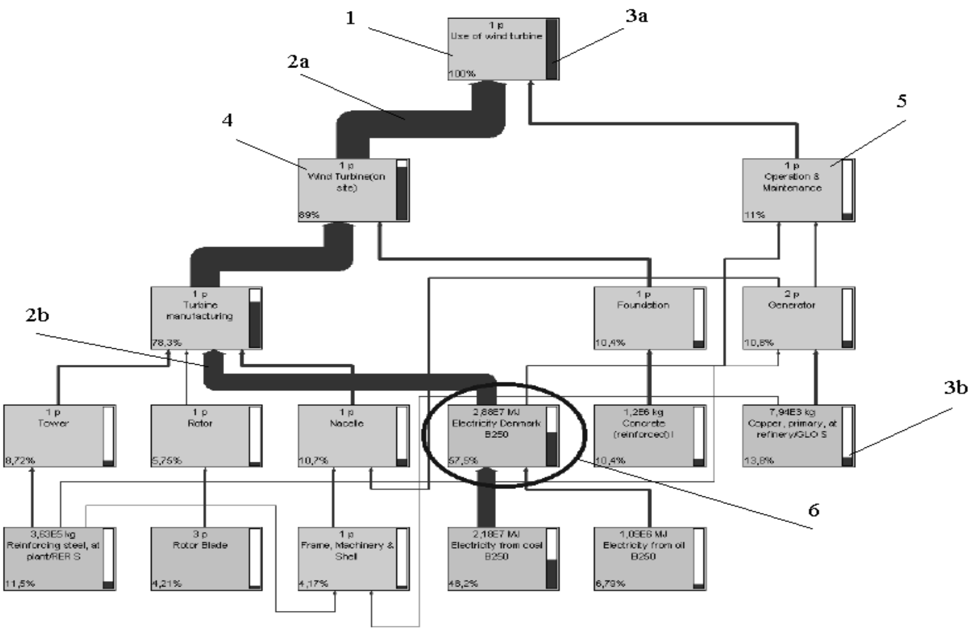

Figure 4. Wind farm life cycle process tree: 1 – the central element; 2a – input flows; 2b - output flows; 3a – red thermometers; 3b – green vertical stripes on the right side of each block – show the load on the environment or its avoidance , which forms each element of the chart;4 – Transport and Erection (Concrete foundation & Assembling) of the turbine on site; 5 – Operation; 6 – Electricity Denmark B250

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A typical Life Cycle Assessment inventory table consists of a few hundred or more items. They might be grouped into categories: raw materials, emissions to air, water, soil, solid emissions, non-material emissions (noise, radiation, land use) etc. An inventory table is a basis for the next step of LCA – impact assessment. The data from an inventory table has to be processed to attain a higher level of aggregation. Ideally the aggregation process results in a meaningful single score

Based on the inventory, in accordance with the defined limits and the data presented in table. 1, SimaPro program generates a process tree to identify potential impacts (Fig. 4).

Figure 4 shows the wind turbine life cycle process tree, based on the data obtained from the Environmental Impact Assessment Report Construction of a 120 MW wind farm on the territory of the Volovets village council of Volovets district and on the territory of the Bereznyky, Dusyno, Nelipyno, and Tybava village councils (outside the settlements) Svalyava district of Transcarpathian region No. 2018821379 of 5 February 2018 p. [40].

Figure 5 shows a typical process block that is necessery for calculating an environmental index and containings material, process or life stage – here: Wind turbine, Quantity – here: one piec 1, Value of the currently calculated quantity – here: partial environmentalindex for this impact and a environmental "thermometer" showes the contribution of a process to the environmental index.

The calculation is made for the element of the wind turbine life cycle.

To analyze the specific stages and their impact on the final output, the "use of wind turbine" flow chart was investigated. The cut-off value was set as 4% and the pointers have the width according to their significance in the final result.

Having examined the chart, it was observed that energy consumption (especially from coal) expressed as electricity Ukraine B250 has a major impact on environment (57.5 %). It can be explained by its affecting the fuels consumption and thus resources mining as well as emission increase (greenhouse gasses, respiratory inorganics etc.) or carcinogens production.

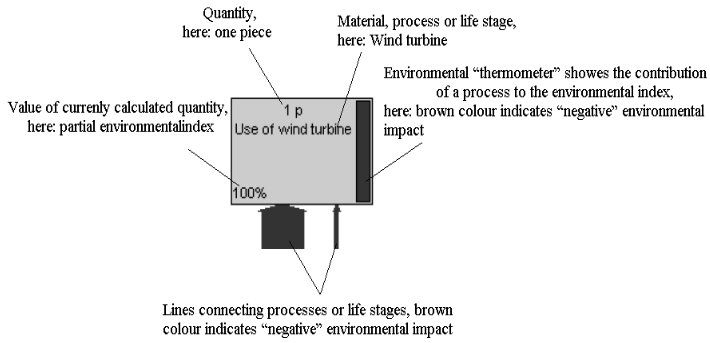

Figure 5. A process box for the calculation of an environmental index

As mentioned earlier in the results Chapter, energy is used for the indispensable processes as manufacturing of different wind turbine parts or transport.

Other stages of the process which have a significant effect on the output are the production of copper and reinforcing steel, having the impact of 13.8 % and 11.5 % respectively. It has to be also pointed out that operation and maintenance processes are of significance as well influencing the total output by 11 %.

The first step to reach higher aggregation of the data is to classify them. The third stage of the study begins with the classification, namely environmental impact assessment of the wind turbine life cycle.

D. *Classification*

Inflows and outflows from the life cycle are gathered in a number of groups representing the chosen impact categories. The inventory table is rearranged in such a way that under each impact category, all the relevant emissions or material consumption are listed (qualitatively and quantitatively).

The common source of uncertainty here is the lack of a universally accepted appropriate official list of environmental impacts to consider. Nevertheless, as a result of numerous already performed LCAs, a "standard", a list of environmental impacts that should be treated does exists. These are all broadly recognised environmental problems such as resource depletion, toxicity, global warming, ozone depletion, eutrophication, acidification, etc. The choice of impact categories is subjective. It should be adjusted to ensure good representation of the environmental burden caused by a product, as the outcome of the LCA strongly depends on the choice of impact categories. The list should, if possible, be made already as a part of the goal and scope definition. There are many other possible impact categories which may be important in some situations, especially in the local scale, and then should be included. Examples are radiation, final solid waste load, noise, smell, and landscape degradation.

Some outputs can be allocated to more than one category, e.g. NO_2 causes both acidification, eutrophication and toxicity.

Thus when performing an LCA, all the emissions and the resource consumption which enter or leave a life cycle are translated into the environmental problems that they potentially may contribute to. The two terms environmental effects and life cycle both need to be properly understood.

After multiplication all emissions are expressed in the same unit, kilograms.

E. *Environmental effects*

are the consequences of a physical interaction between a system studied and the environment. In practical use all environmental effects are represented by several categories of environmental problems. The most commonly used are:

- Resource depletion;

- Global warming;
- Ozone depletion;
- Human toxicity;
- Ecotoxicity;
- Photochemical oxidation;
- Acidification;
- Eutrophication;
- Land use;
- Others (including solid waste, heavy metals, carcinogens, radiation, species extinction, noise).

In the previous step, substances contributing to the impact categories were taken from an inventory table and ascribed to a certain group. However, different substances among one group contribute differently to the impact category. During the characterisation step the relative strength of the unwanted emission is evaluated and contributions to each environmental problem are quantified. What is needed here is a single number for each category.

The computational procedure used for aggregating the data among one impact category may be explained by the example for global warming. The characterisation can be performed on the basis of environmental models, which allow us to compare different substances contributing to the same environmental problem. This is done by applying so-called equivalence factors. An equivalence factor indicates how many times more a given compound contributes to a problem in comparison to a chosen reference substance. In case of global warming CO_2 is chosen to be the point of reference. All the other substances causing an enhanced greenhouse effect are given a coefficient indicating how many times more or less these compounds contribute to the effect. For example, methane has an equivalence factor of 11, which means that 1 kg of methane causes the same greenhouse effect as 11 kg of carbon dioxide. The result is expressed in the equivalent amount of CO_2. When the equivalence have been calculated all the figures in the impact category have a common unit and can be added up.

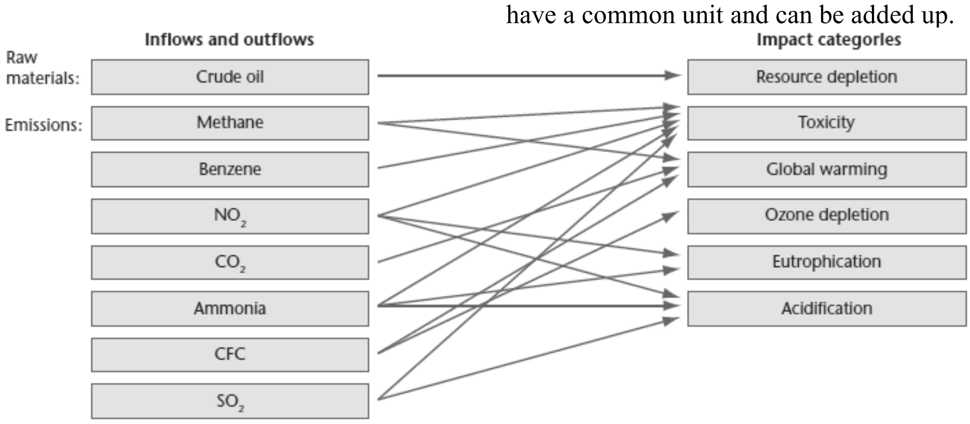

Figure 6. Relations between emissions and impact categories. To the left are raw materials used (top) and pollutants emitted (bottom) during the life cycle of a product. To the right are the impact categories to which these emissions contribute. The figure illustrates that one emission may contribute to several impacts, and that several emissions contribute to the same impact

The electricity consumed during the manufacture of wind turbine is the largest contributor to the *climate change* (Figure 7) with 85 % out of total 1.58 DALY. This is because electricity production in Ukraine is mainly based on the use of coal as fuel [35], which definitely results in carbon dioxide emissions. Due to the reduction of coal in the primary energy sources, the current impact on climate change is smaller than the LCA model presents. The production of reinforcing steel is the second largest contributor, however, very minor compared to electricity from coal. The recycling of steel and iron from the wind turbine has positive impact on climate change, since it substitutes production of 334 tons iron with reduction in energy consumption.

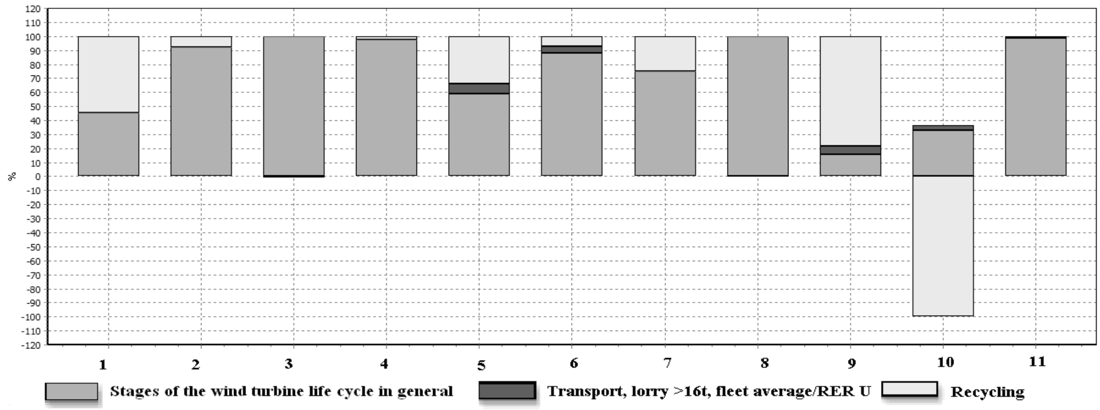

Figure 7. Characterization of the impacts of the life cycle of a wind farm according to the methodology Eco-indicator'99:

1 – Carcinogens; 2 – Resp. organic; 3 – Resp. inorganic; 4 – Climate change; 5 – Radiation; 6 – Ozone layer; 7 – Ecotoxicity; 8 – Acidification/Eutrofication; 9 – Land use; 10 – Minerals; 11 – Fossil fuels

The impact of the use of wind turbine amounts 2.14 DALY. However, implementing the waste scenario (- 0.883 DALY) decreases this value to the total impact of 1.25 DALY (by 41 %, see Figure 7). Electricity from coal contributes most to the *carcinogenic* effect, followed by steel production and copper production (Figure 7). Because the recycling includes all steel and iron. The reduction of carcinogens in recycling steel and iron (0.41 DALY) is larger than production of reinforcing steel (0.38 DALY). The main substances responsible for this are emitted to water Arsenic ions (0.81 DALY) and unspecified metallic ions (0.028 DALY), to air unspecified metals (0.342 DALY), Cadmium (0.06 DALY) and Arsenic (0.27 DALY).

The electricity from coal is the largest contributor of *respiratory inorganics* (Figure 7). The concrete for wind turbine's foundations has serious impacts on respiratory systems. The particulates, nitrogen dioxide and sulfur dioxide (2.33, 1.65 and 1.51 DALY respectively) are the main threats to human respiratory health. Using the waste scenario decreases the emissions of the inorganic substances by 15.4 % making it the total impact of 5.91 DALY.

Fossil fuels as coal, oil, and gas, are mainly used to generate electricity. The production of metal, e.g. steel and iron is very energy consuming. Therefore, the production of reinforcing steel becomes the third largest fossil fuel user. The transportation of raw materials and components of wind turbine and the erection consume a substantial amount of diesel which is expressed in Figure 7 as crude oil.

Respiratory organics. The waste scenario is not helpful in this case as it contributes in the negative environmental impact as well by 5,93 %. The total emissions amounts 33,2E-4 and the main ones are non-methane volatile organic compounds (25,2E-4) as well as methane and unspecified and aromatic hydrocarbons all amounting 7,45E-4.

The reduction of the *radiation* amounts 16,5 % while using the waste scenario with the total impact caused by the wind turbine of 3,79E-3. It is caused mostly by Radon-222 and Carbon-14 both present in the air. Their radiation amounts 2,55E-3 and 1,22E-3 respectively.

Ozone layer. This category is the second one on which the waste scenario has negative impact as it contributes in 7,34 % in the total impact, which amounts 5,27E-4. It is caused mainly by one substance – bromotrifluoromethane (BTM), known as well as Halon 1303, whose impact amounts 5,02E-4 D.

Ecotoxicity. It is the second biggest positive impact of the waste scenario on the final result. It reduces the environmental impact by 47,8 %. After that total impact amounts 2,32E6 PAF × m^2 × yr and the biggest contribution in it have unspecified metals (1,25E6) as well as Nickel, Zinc (6,33E5 together) and Lead (9,64E4), all contained in the air.

Acidification/ Eutrophication. The waste scenario has a small impact on reducing the negative one of the use phase. It decreases the impact by 4,07 % making it 1,38E5 PDF×m^2×yr in total. The substances responsible for that number are nitrogen oxides and sulfur oxides amounting 1,06E5 and 2,88E4 respectively.

Land use. Waste scenario is very helpful in this case as it minimizes the negative impact by 32,3 %, so the total impact amounts 3,1E4 PDF × m^2 × yr. It is influenced mainly by industrial area occupation (1,3E4) and transformation to industrial area (9,18E3). It needs to be said that thanks to the waste scenario the dump site occupation is reduced by 1,46E4 and influences the most the impact decrease.

Minerals. This category is influenced by the waste scenario at most. It decreases the negative impact by 79,1 % and makes it 1,01E5 MJ surplus in total. Thus, the negative impact is caused mainly by two minerals: nickel (1,98 % in silicates, 1,04 % in crude ore); copper (0,99 % in sulfide, Cu 0,36 % and MO 8,2E-3 % in crude ore). They amount 6,47E4 and 3,68E4 MJ surplus respectively.

As we can see the waste scenario has different impacts in each category, of which three can be marked out as the most influenced ones: Mineral, Ecotoxicity and Carcinogens. It is caused by the fact that almost 80 % of wastes (excluding concrete) were recycled. That allowed reusing received minerals, mainly copper, iron and aluminum, and obviously decreased their mining but also delimited the emission of elements such as Cadmium, Nickel, Lead or Arsenic – produced during that process.

Unfortunately, the waste scenario is not just improving the cycle, but it has the negative impact as well. This can be explained by the fact that during the recycling process many gases are emitted, which in consequence can lead for instance to ozone layer reduction.

Characterisation is easy if all substances contributing to each impact category are known and a reference substance as well as equivalence factors have been defined. For many of the environmental impacts, the equivalence factors remain controversial with regard to the methodology by which they are calculated. This applies especially to the categories which are difficult to describe, e.g. "human health". Nevertheless, there are established equivalence factors for the main environmental problems (Table 2).

TABLE II. EQUIVALENCE FACTORS FOR ENVIRONMENTAL IMPACTS

Classification of environmental impact	Equivalence factor and reference substance	
Ozone depletion	Ozone Depletion Potential	CFC-11 equivalents
Acidification	Acidification Potential	SO_2 equivalents
Eutrophication	Eutrophication Potential	Phosphate equivalents
Photochemical smog creation	Photochemical Ozone Creation Potential	ethylene equivalents

The contribution to an environmental impact is calculated for any substance if an equivalence factor is available.

The final result of the characterisation step is a list of potential environmental impacts. This list of effect scores, one for each category, is called the environmental profile of the product or service.

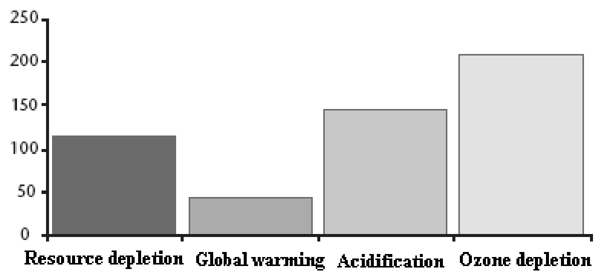

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Figure 8. Environmental profile of the entire wind turbine life cycle

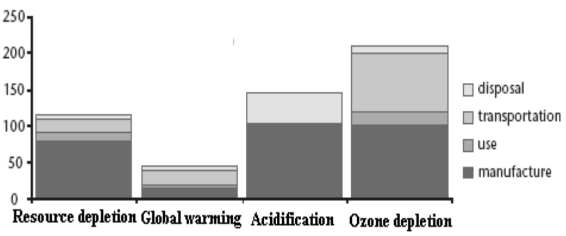

Figure 9. Environmental profile taking into account the stages of the wind turbine life cycle

In two graphs, Figs. 8 and 9, the environmental profiles of wind turbines are shown. These are sets of four single scores, one for each of four impact categories: resource depletion, global warming, acidification and ozone depletion. Figure 9 presents single time estimates divided into four life cycle stages: manufacture, use, transportation and disposal. It allows us to identify immediately the life cycle phases which have a significant environmental impact. For example manufacturing contributes greatly to resource depletion. The results from the characterisation step cannot be compared since they are usually presented in different units (CO_2eq., SO_2eq., CFC-11eq, etc.). A procedure to allow us to compare impact categories among themselves is therefore carried out.

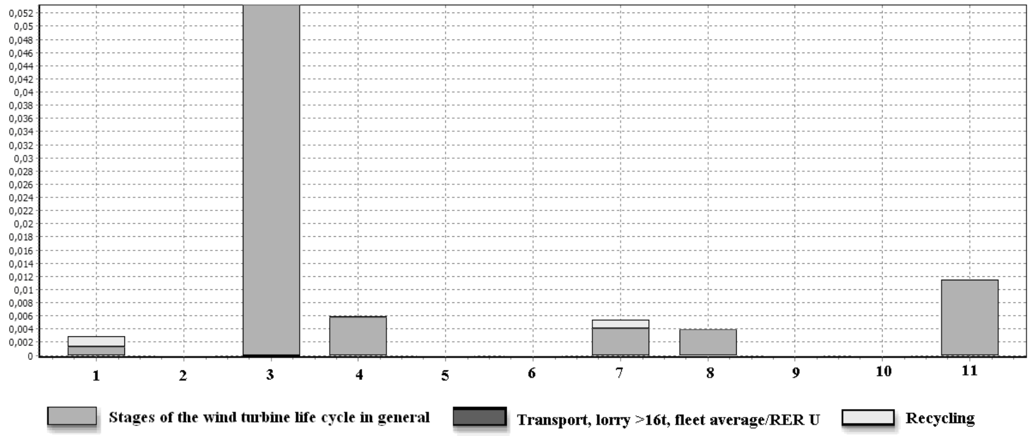

Figure 10. Normalized estimation of the effects of the wind farm life cycle by the method Eco-indicator'99

1 – Carcinogens; 2 – Resp. organic; 3 – Resp. inorganic; 4 – Climate change; 5 – Radiation; 6 – Ozone layer; 7 – Ecotoxicity; 8 – Acidification/Eutrofication; 9 – Land use; 10 – Minerals; 11 – Fossil fuels

From a normalized environmental profile (Fig. 10), for example, we can conclude that the respiratory inorganic is 0.052% of all CO_2 equivalents in the life cycle of a wind turbine. Thus, we can say that the life cycle of wind turbines contributes more to global warming than to the destruction of the ozone layer and almost does not affect the flora in the region of construction and operation of wind turbines.

F. Normalisation

Normalisation is performed to make the effect scores of the environmental profile comparable. The normalised effect score is the percentage of a given product's annual contribution to that effect in a certain area [40]:

$$\text{Normalized effect score} = \frac{\text{annual contribution to that effect in a certain area}}{\text{effect score for a given category}} \quad (1)$$

The figures 8, 9 do not indicate, however, which impacts are of the highest priority, i.e. one cannot say that global warming is a more serious environmental problem than ozone depletion nor the other way around. The environmental profile is only put in a broader context, which makes the interpretation easier.

The lack of relevant figures representing annual contributions to environmental problems is the main difficulty in the normalisation step. The figure 10 shows the environmental load of the impact categories which where chosen for the analysis. As it can be observed there are two categories which are of greatest importance both from the total impact and waste scenario significance.

Respiratory inorganics such as nitrogen and sulfur oxides and many more have the largest impact on the environment with the total amount of 454 points. They are emitted mostly during the fuel burning. However, it has to be pointed out that the waste scenario is the most significant as far as this category is concerned. Even though minerals' impact is decreased by almost 80% and inorganics by 'just' 15, the final output shows that the latter amount is bigger when compared with a common unit.

The second biggest environmental impact is fossil fuels – 365 points. This is caused mainly by the use of electricity during the whole process, which is produced from coal in the first place, but also from oil and gas. The contribution of alternative resources (hydro, uranium) is minor. Obviously, the consumption occurs on the very early stage of the process, but does influence the further ones where the consumption is highest – manufacturing of the turbine's parts and transport.

The high impact on the climate change is also alarming. It should be regarded as global warming which is caused by greenhouse gases as carbon dioxide or methane and can result in the change of sea level, precipitation distribution or increased intensity of weather disasters such as hurricanes.

G. Weighting

is the most difficult, subjective and contradictory stage of assessment because it is based not on the natural sciences but on subjective considerations. To compare the effects, weighting factors are used by default which are determined by the following methods:

- by Expert Group Decision – Eco-indicator 99 and ReCiPe methods;
- method of accounting for distance from the target – Ecological Scarcity methods;
- in accordance with monetary damage assessment – EPS 2000 method.

An alternative approach to comparing impacts is proposed by Hofstetter et al. (1999) [41–44]. This approach is implemented in SimaPro. It consists in comparing the environmental friendliness of products / processes / services for all possible combinations of weighting factors for three categories of harm: human health, the quality of ecosystems and resources. For each combination of weighting factors – the corresponding point of the comparison triangle – the sum of these coefficients is 100%.

H. For the Eco-indicator'99 Method

it is accepted that the impacts on health and ecosystems are twice as important as the impact on resources, according to this, the weighting factors are 40%, 40% and 20% [41]. The program calculates the environmental load for all possible values of the weighting factors.If the comparative assessment of the environmental friendliness of the products under consideration is affected by the ratio of the weight of the comparison criteria, then both alternatives are displayed in the comparison triangle with the conditions for occurrence of their advantage being reflected (Fig. 11).

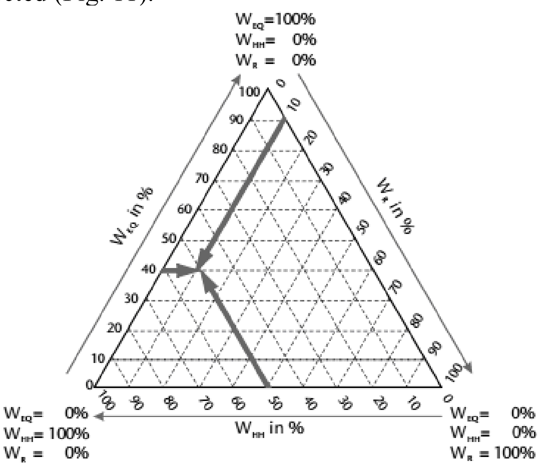

Figure 11. The weighting triangle: W_{EQ} – Weighting factor for the damage to ecosystem quality; W_{HH} – Weighting factor for the damage to human health; W_R – Weighting factor for the damage to energy resources; $W_{EQ} + W_{HH} + W_R = 100\%$

Ranking impact categories in terms of their environmental impact makes clear distinction between the weighting and all of the previous phases. The latter use empirical knowledge of environmental effects and their mechanisms, while the weighting relies mainly on preferences and social values. In practice, weighting is performed by multiplying a normalised environmental profile by a set of weighting factors, which reflect the seriousness of a given effect. One of the ready-made methods, Eco-indicator 95, can serve an example of a defined set of weighting factors (Table 3).

TABLE III. WEIGHTING FACTORS USED IN ECO-INDICATOR 95

Impact category	**Weighting factor**
Greenhouse	2.5
Ozone layer	100
Acidification	10
Eutrophication	5
Heavy metals	5
Carcinogens	10
Winter smog	5
Summer smog	2.5
Pesticides	25

As it can be concluded from the table, the highest priority is given to ozone layer depletion and emissions of pesticides. If each impact category is provided with a factor according to its environmental significance, an environmental profile can be expressed in a single *environmental index*. An environmental index is a sum of the numbers, which a weighted environmental profile consists of. Once the environmental indices are calculated, comparisons of products are easy. Let us assume that product A is represented by an environmental index of 5 and product B has an environmental index of 10. One can conclude that A is twice as environmentally friendly as B. The main difficulty lies, however, in the fact that there is no broadly accepted methodology for establishing weighting factors. For the time being it is difficult to rank environmental problems without running the risk of criticism.

Then follows the critical issue: what should be considered an environmental problem. In the Eco-indicator approach three damage categories, so-called endpoints, are distinguished: Human Health, Ecosystem Quality and Resources (Figure 12).

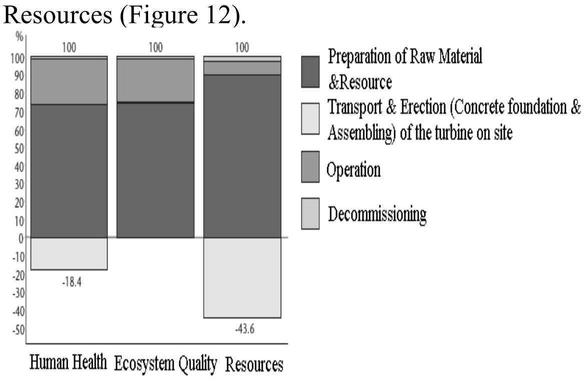

Figure 12. Evaluation of the impact of the life cycle of wind turbines by three combined categories for each stage of the life cycle

The three categories are not sufficiently self-explanatory, and a description of what is included in each of the three terms is necessary for building up the methodology.

Figure 13 shows in general the Eco-indicator methodology. The white boxes refer to the procedures; the other boxes refer to the (intermediate) results. The health of any human individual, being a member of the present or a future generation, may be damaged either by reducing the duration of his or her life by premature death, or by causing a temporary or permanent reduction of body functions (disabilities).

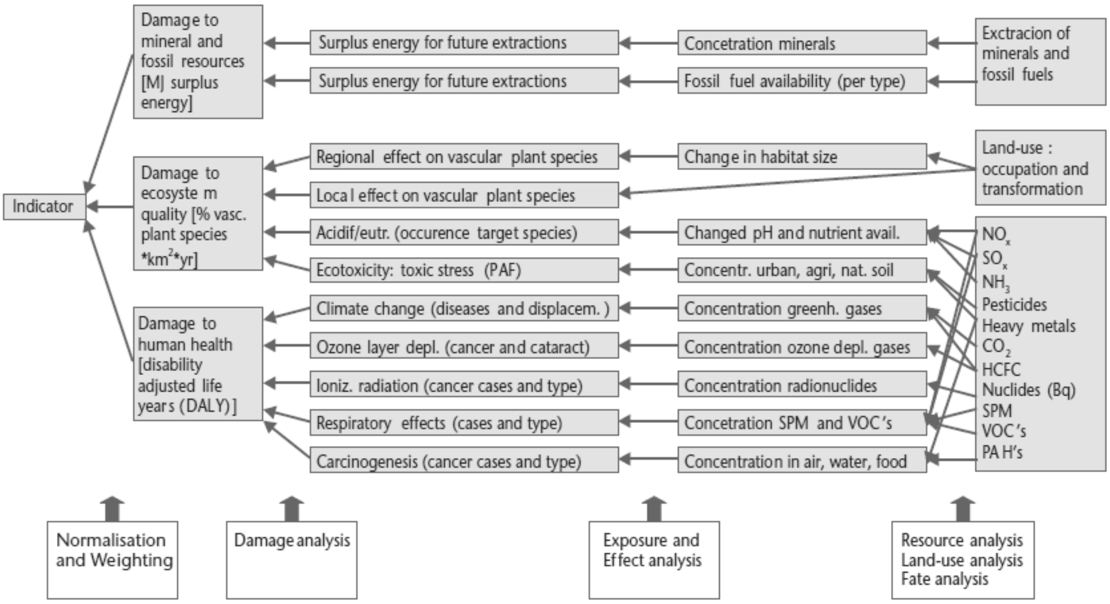

Figure 13. Eco-indicator methodology [45]

The environmental sources for such damages include e.g.:

- Infectious diseases, cardiovascular and respiratory diseases, as well as forced displacement due to the climate change.
- Cancer as a result of ionizing radiation.
- Cancer and eye damages due to ozone layer depletion.
- Respiratory diseases and cancer due to toxic chemicals in air, drinking water and food.

These types of damages represent important threats to Human Health caused by emissions from product systems. The damage category is, however, far from complete. For instance, health damage from emissions of heavy metals such as Cd and Pb, of endocrine disrupters etc. as well as health damages from allergenic substances, noise and odour are not yet modelled in Eco-indicator 99.

Ecosystems are very complex, and it is very difficult to determine all damage inflicted upon them. An important difference compared with Human Health is that even if you could, you are not really concerned with the individual organism, plant or animal. The species diversity is used as an indicator for Ecosystem Quality. You can express the ecosystem damage as a percentage of species that are threatened or that disappear from a given area during a certain time.

For ecotoxicity, Eco-indicator 99 uses a method developed in the Netherlands for the Dutch Environmental Outlook [46]. This method determines the Potentially Affected Fraction (PAF) of species in relation to the concentration of toxic substances. The PAFs are determined on the basis of toxicity data for terrestrial and aquatic organisms like microorganisms, plants, worms, algae, amphibians, mollusks, crustaceans and fish.

The PAF expresses the percentage of species that is exposed to a concentration above the No Observed Effect Concentration (NOEC). A higher concentration caused a larger number of species that are affected. The PAF damage function has a typical shape as shown in figure 14. A Logistic PAF-curve expresses the potential affected fraction of species at different concentrations of a substance. When a chemical is emitted in an area, its concentration in the area will increase temporarily. This change in concentration will cause a change in the PAF value. The damage caused by the emission of this substance depends on the slope of the curve in a suitably chosen working point.

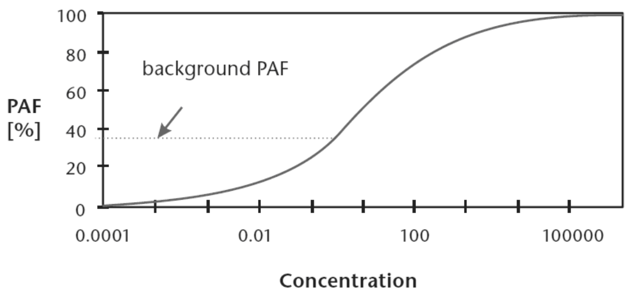

Figure 14. The PAF-curve, Potentially Affected Fraction of species as a function of the concentration of a single substance (%) [44]

Being based on NOEC, a PAF does not necessarily correspond to an observable damage. Even a high PAF value of 50 % or even 90 % does not have to result in a really observable effect. PAF should be interpreted as toxic stress and not as a measure to model disappearance or extinction of species.

For *land use*, Eco-indicator 99 also uses the Potentially Disappeared Fraction (PDF) as an indicator. In this case however, you do not consider target species but all species. The damage model is rather complex, and include four different models:

- The local effect of land occupation.
- The local effect of land conversion.
- The regional effect of land occupation.
- The regional effect of land conversion.

The local effect refers to the change in species numbers occurring on the occupied or converted land itself, while the regional effect refers to the changes on the natural areas outside the occupied or converted area. The regional effect was first described by [46]. The data for the species numbers per type of land-use and some of the concepts used for the local effect are based on [47].

The data on the species numbers are based on observations, and not on models. The problem with this type of data is that it is not possible to separate the influence of the type of land use from the influence of emissions. For this reason special care must be taken to avoid double counting of effects which are included in land-use and which could be included also in other damage models.

The Ecosystem Quality damage category is the most problematic of the three categories, as it is not completely homogeneous. As a temporary solution one may combine PAF and PDF.

In the case of non-renewable resources (minerals and fossil fuels), it is obvious that there is a limit on the human use of these resources, but it is rather arbitrary to give data on the total quantity per resource existing in the accessible part of the earth crust. The sum of the known and easily exploitable deposits is quite small in comparison with current yearly extractions. If one includes occurrences of very low concentrations or with very difficult access, the resource figures become huge. It is difficult to fix convincing boundaries for including or not-including occurrences between the two extremes, as quantity and quality are directly linked.

To tackle this problem, the Eco-indicator methodology does not consider the quantity of resources as such, but rather the qualitative structure of resources.

Chapman and Roberts [48] developed an assessment procedure for the seriousness of resource depletion, based on the energy needed to extract a mineral in relation to the concentration. As more minerals are extracted, the energy requirements for future mining will increase. The measure of damage used in the Eco-indicator for resource extraction is based on this work. It is the energy needed to extract a kg of a mineral in the future. Much of the data is supplied by [49].

The Eco-indicator values for a certain impact are expressed as a sum of impacts for each of the three categories. Each of the impact categories are expressed in one unit. Impact on human health is expressed as DALY, Disability Adjusted Life Years, that is the number of years of life lost and the number of years lived disabled. Impact on ecosystem quality is expressed as the loss of species over a certain area during a certain time PDF × xm^2 × year. Depletion of resources is expressed as surplus energy needed for future extractions of minerals and fossil fuels.

VI. Conclusions

The goal of assessing the life cycle of wind turbines has been fully achieved through this study. We analyzed the entire life cycle starting form the manufacturing phase to the disposal phase and established all the environmental effects associated with the wind turbine throughout its whole lifetime.

The waste scenario is a very important phase of the life cycle of the wind turbine. With recycling of the materials we are able to reduce the negative environmental impacts greatly. In other words, without recycling wind turbines have greater negative environmental impacts.

The manufacturing phase is a very crucial phase in the life cycle of the wind turbine because it yields the biggest environmental impacts. This is particularly due to the type of electricity used. The more "green" the source of electricity used in the manufacturing phase of the wind turbine; the less the environmental impacts of the wind turbine.

The analysis showed that although most of the products have been recycled and minerals could have been used again, it is still fossil fuels which influence the resource the most and this matter should be considered accordingly in the system improvement.

It was difficult to tell which specific process was energy intensive in the manufacturing process because the energy results were given as a sum total for the whole manufacturing process.

We assumed that the electricity used to manufacture wind turbines is any energy (coal + gas + oil + lignite + hydro). This influenced the results greatly since the impacts in the manufacturing phase depend on the type of electricity used. When hydro power was selected as the source of electricity to manufacture the wind turbine, the negative impacts on the environment would be less.

The energy consumption for manufacture of wind turbine is largest impact contributor in various characterization categories. It is worth investigating the manufacture process in depth to find out opportunities to improve energy efficiency.

It needs to be pointed out that the wind turbines also have a visual impact on the environment. However, due to its subjective nature, the category was omitted.

Lastly, the impacts of the wind energy have been compared to those created by the other energy sources – coal, oil and hydro. The aim was to find out whether the wind energy is actually as 'green' as advertised or it is just a myth. It appeared to be very competitive as far as environmental impacts are concerned, exceeding meaningfully the coal and oil energy. Although hydro power occurred to be more environmentally friendly, the difference is just slight and both those energies should be undoubtfully regarded as the next step to achieving the sustainable development.

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