

**Life Cycle Assessment**

**1N1800**

# **Life Cycle Assessment of a Wind Turbine**

**Group 7**

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# Life Cycle Assessment for Wind Turbine

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# Life Cycle Assessment for Wind Turbine

## 1. Goal and Scope

### 1.1 Goal of the study

Assess the life cycle of wind turbine and compare its environmental impacts with the impacts of other energy sources (oil, coal and hydro).

### 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 [5]. 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.

### Reasons for Carrying out the Study

So the aim of this project is to assess the environmental effects during the whole life cycle of the wind turbine (from raw material extraction to waste management). Therefore this study intends to look at the details of all the phases in order to establish all the environmental effects associated with the wind turbine throughout its whole lifetime.

### Comparative LCA

Except from the LCA of the wind turbine, the report presents the comparison between four different energy sources: coal, oil, hydro and wind.

### Focal question

What are the environmental impacts of wind turbines with regard to their entire life cycle?  
What are the environmental impacts of wind turbines in comparison to other energy sources?

### Change-oriented or accounting LCA

This LCA is the accounting type as opposed to the change-oriented type.

### Intended application of LCA results

In addition to the academic intention of this study, the results of this analysis could be employed by authorities such as politicians and policy makers that want to promote sustainable and renewable energy sources and know the environmental effects of the wind power as compared to other energy sources.

Furthermore wind turbine manufacturers could be interested in producing more “green” turbines through improvement strategies such as: minimizing the resource consumption (more

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recycling, use of less pollutant materials etc.) and maximizing the energy production of a wind turbine.

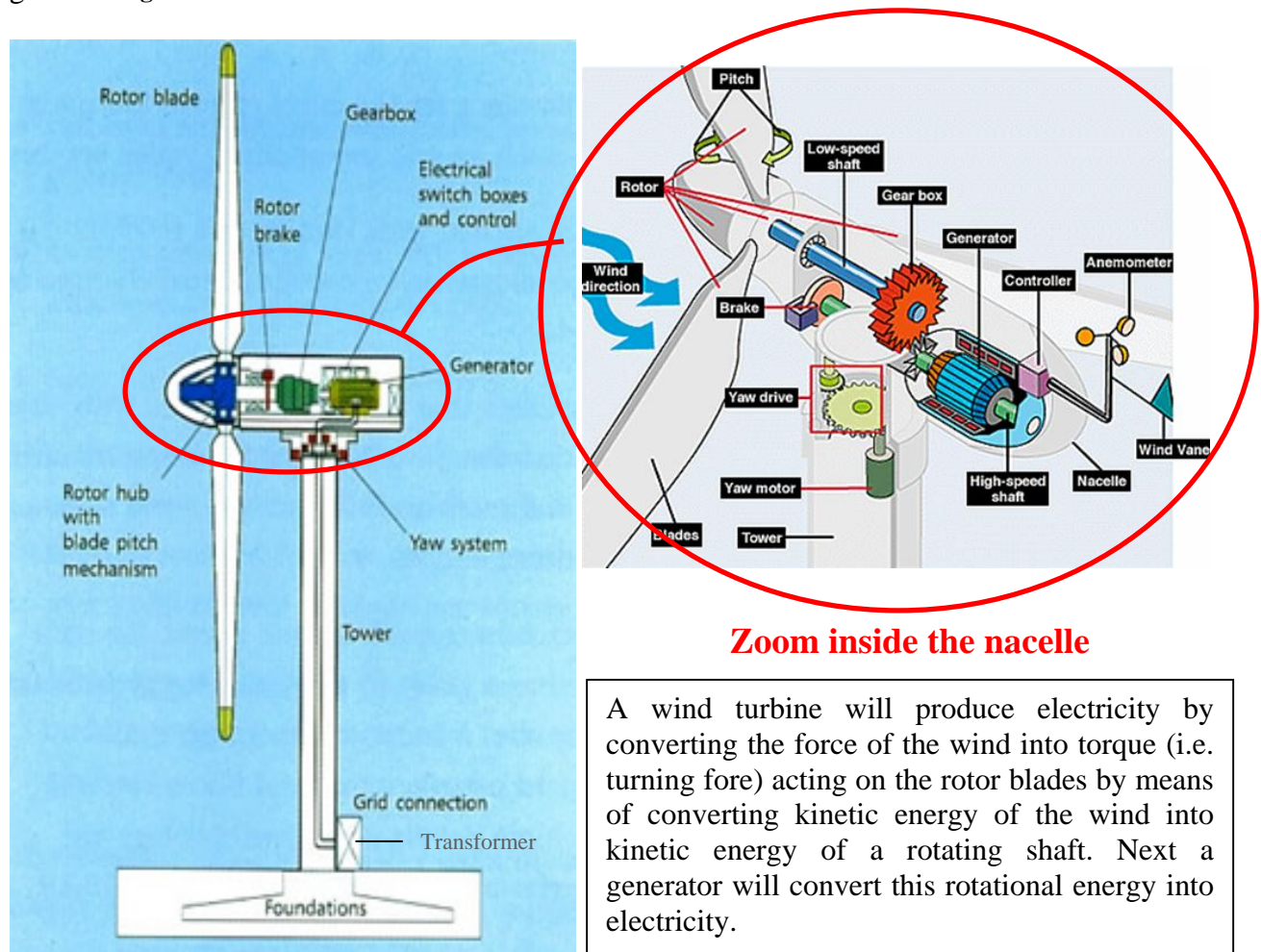
### Intended audience

The intended audience for this LCA is mainly all the parties involved in the manufacture and use of wind turbines, environmental consultants, and energy experts etc. The general public could also benefit from knowing the environmental effects of using wind turbines as an energy source.

### Studied product

Vestas V90-3.0 MW onshore wind turbine is selected as the subject of study because it is one of the mainstream large wind turbines with installations in various regions.

In order to make sure that there will be no misunderstanding with the different names of the main parts and components of a wind turbine, a typical sketch of an onshore wind turbine is given in **Figure 1**.



**Figure 1. Main parts and components of a wind turbine**

[Source: [www.kidwind.org/images/wind\\_turbine\\_drawing.jpg](http://www.kidwind.org/images/wind_turbine_drawing.jpg) (on the left), [www.daviddarling.info/images/wind\\_turbine.gif](http://www.daviddarling.info/images/wind_turbine.gif) (on the right)]

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## 1.2 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. Vestas [10] stated in that one Vestas V90-3 MW onshore wind turbine generates 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 [7]) of 30.02 %, which means 157,800 MWh electricity generated in its life span of 20 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.

## 1.3 System boundaries

The system boundaries considered in this report are defined according to:

### **Boundaries in relation to nature**

In this LCA, we are taking into account the entire life-cycle of the wind turbine, from the raw material extraction to the moment they totally lose their value (land filling or recycling). Maintenance and decommissioning of the wind turbine is therefore included in the study, since these phases are part of the lifetime of the wind turbine.

We will limit our study to only on-shore wind turbines and exclude the off-shore wind turbines because of the difference in values of the impacts and their significance for the different types of wind turbines. Our focus will be on the large on-shore wind turbines (as large turbines are used to produce electricity at a “big scale”): specifically a 3MW wind turbine will be assessed in this LCA, because they are the ones that will be currently used in this range of large turbine.

The material production phase includes the extraction of the raw materials as well as the materials manufacture, which is the processing of the raw materials into intermediate materials. This phase also includes transportation of raw materials to the location where they are processed into intermediate materials as well as transportation of the intermediate materials to the construction site of the wind turbine. The transportation of the waste materials and old parts is included in the maintenance and decommissioning phase.

### **Geographical boundaries**

Denmark is the geographical limit in this LCA. However the location of the wind turbine in terms of: low, medium or high wind speed will affect how much “green energy” will be produced during the life of the turbine. In this LCA we have chosen a location suitable for wind farm, which means relatively high wind speed.

### **Time horizon**

The time horizon considered in this study is the life time of the wind turbine which is 20 years.

### **Cut-off criteria**

One of the cut-offs performed in the study is the omission of the “transmission” stage of the energy produced by the wind turbine, since it is considered that the transmission of electricity from any energy source would be the same.

# Life Cycle Assessment for Wind Turbine

## Allocation procedures

There is no allocation problem in the manufacture and operation of the wind turbine because only one product is produced.

## 1.4 Assumptions and limitations

Due to the difficulty in collecting relevant data and the time constraints, we had to resort to some assumptions to make this analysis easy to accomplish. The assumptions that were made are further explained in section 2.2.2 Data used in SimaPro.

## 1.5 Software

The software used in this study is SimaPro 6.0 made by Pre Consultants.

## 1.6 Impact categories and impact assessment method

The impact categories that are considered in this model are:

- Climate change (Emissions to air like hydrocarbons, carbon dioxide, methane etc.)
- Carcinogens (Arsenic, Benzene, Cadmium, Heavy metals etc.)
- Respiratory inorganics (Emissions to air, SO<sub>2</sub>, NO<sub>x</sub>)
- Fossil fuels
- Respiratory organics (Emissions to air, all kind of organics)
- Ozone layer (Ozone depletion potential)
- Ecotoxicity (Emission to water, air and soil)
- Acidification/Eutrophication (Emissions to air, Nitrogen, Ammonia etc.)
- Land use
- Minerals (Aluminum, Iron, Lead, Copper etc.)

The first four categories are discussed more precisely in this report as they have the biggest contribution to the total environment impact of the wind turbine (see Figure 9) and the additional graphs are presented for them.

The method chosen due to the relevance of the impact factors for the study is Eco-indicator 99 (H) V2.03.

## 2. Life Cycle Inventory Analysis

### 2.1 Process Flowchart

Figure 2 (See next page) 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”.

# Life Cycle Assessment for Wind Turbine

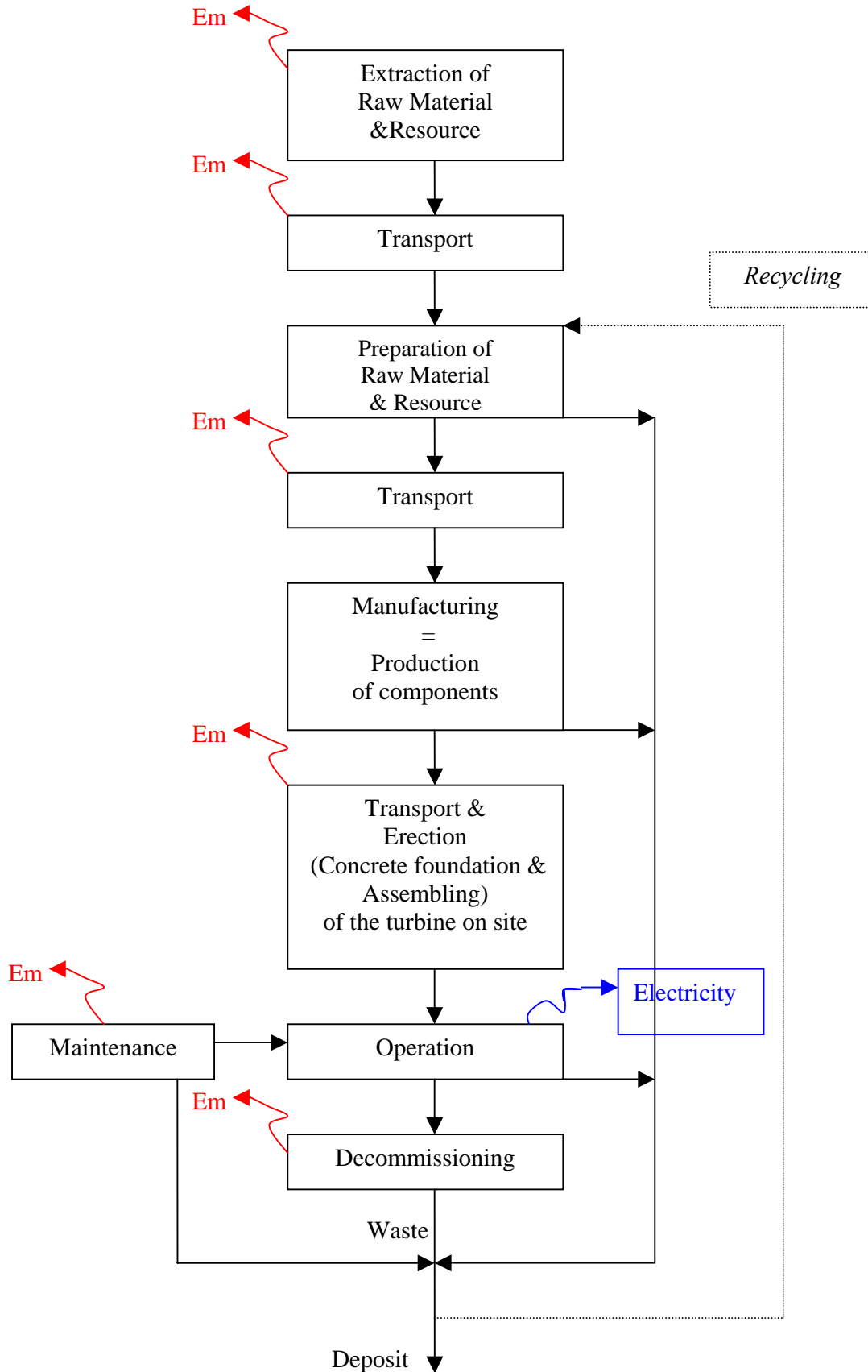


Figure 2. Flowchart of wind turbine life

# Life Cycle Assessment for Wind Turbine

## 2.2 Data

### 2.2.1 Model used in SimaPro (See Figure 3)

### 2.2.2 Data used in SimaPro

## USE OF THE TURBINE

Most of the data used in our model comes from an LCA report realized by Vestas [10] and from the 'General Specification of the V90 Vestas Wind turbine' [8] and from the 'Materials and Manufacturing Fact Sheet of the V90 Vestas Wind turbine' [1] and from the 'Environmental Statement 2004' of Vestas [9].

### ○ **Turbine Manufacturing**

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 [9]. 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.

#### - **Manufacture of the tower:**

The tower is made of plates of steel and it has been assumed that the tower is made of 100 % steel [10].

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 [8].

Limitation: The painting of the tower has not been taken into consideration in our model.

#### - **Manufacture of the rotor:**

The rotor is composed of 3 blades, the hub and the nose cone.

### Life Cycle Assessment for Wind Turbine

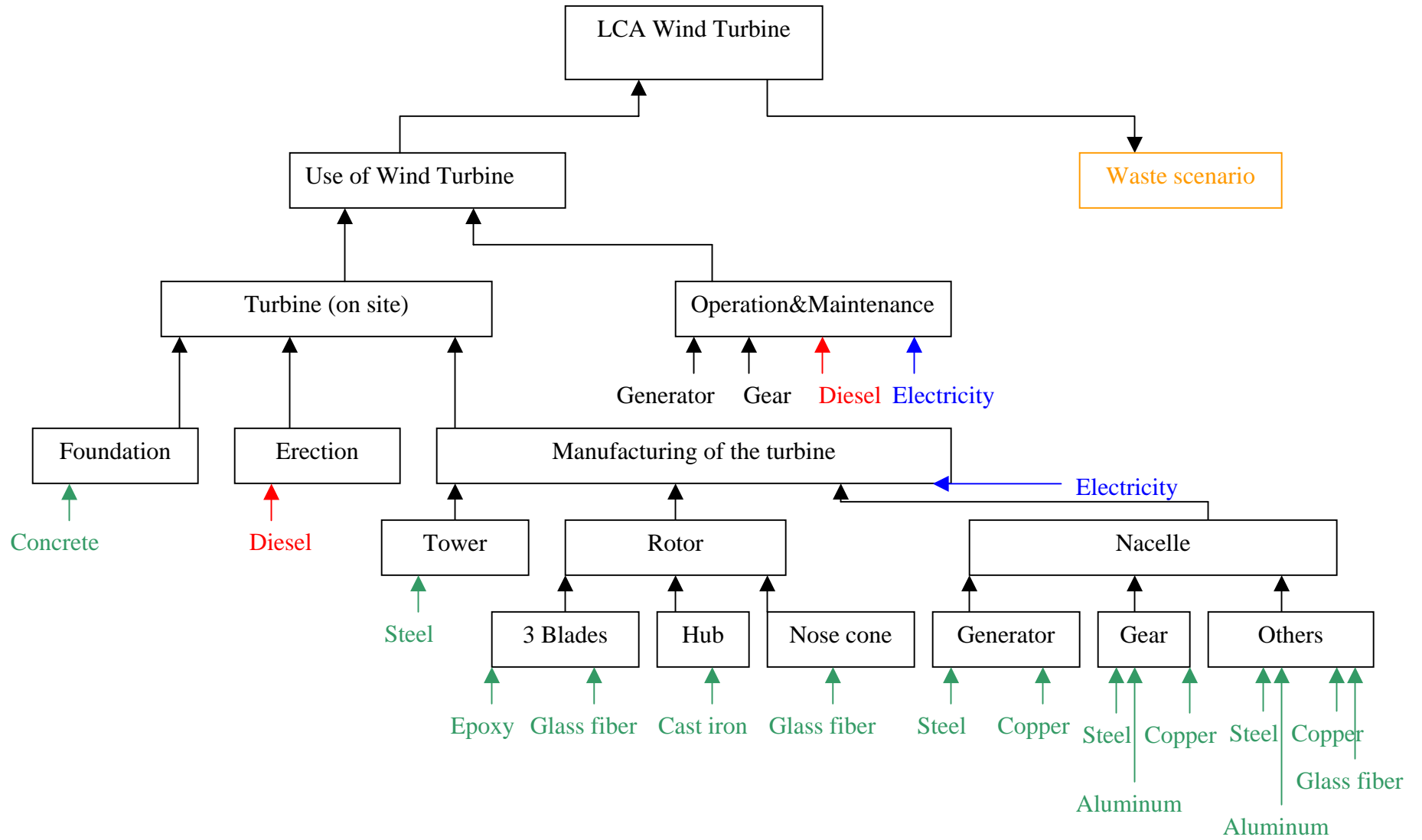


Figure 3. Model for wind turbine in SimaPro

## Life Cycle Assessment for Wind Turbine

- **Manufacture of one blade:**

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 [10].

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) [10] & [8].

Limitation: 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.

- **Manufacture of the hub:**

The hub is made of cast iron and weighs 8.5 tons [8]

Cast iron, at plant/RER S from the data base Ecoinvent system process has been used in SimaPro.

- **Manufacture of the nose cone:**

The nose cone is the shell that will recover the hub. The total weight of the hub and the nose cone is 20 tons [8], 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.

Limitation: Again the painting of the nose cone has not been taken into consideration in our model.

- **Manufacture of the nacelle:**

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)

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- **Manufacture of the generator:**

The generator weight is given to be 8.5 tons [8].

It is assumed to be composed of 35% copper and 65% steel [3].

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.

Limitation: 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.

- **Manufacture of the gear:**

The gear system (called as well gearbox) has a total weight of 23 tons [8].

It is assumed to be composed of 98% steel, 1% copper and 1% aluminum [1].

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.

- **Manufacture of the frame, machinery and shell:**

This unit has a given weight of 37 tons [10].

It is assumed to be composed of 85% steel, 8% aluminum, 4% copper and 3% Glass Reinforced Plastic [1].

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.

Limitation: This unit is composed of so many different components (nacelle cover, transformer, electronics, shaft...) that all the data for each component

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were not available. The above model is based on accounting of the main materials used and their percentage regarding the total weight of the unit.

### ○ **Wind Turbine (on site)**

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 built on the site; and finally the different parts of the turbine (tower, rotor and nacelle) have to be erected and assembled.

#### - **Manufacturing of the turbine:**

See above

#### - **Foundation:**

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 [10].

Concrete (reinforced) I from the data base IDEMAT 2001 has been used in SimaPro.

Limitation: The energy to realize the excavation of the hole has not been considered.

#### - **Erection:**

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 [9] 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.

### ○ **Use of Wind Turbine**

The phase "Use of wind turbine" includes the phase of operation and maintenance of the wind turbine (onsite).

#### - **Wind turbine (on site):**

See above

#### - **Operation and maintenance:**

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.

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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 [9]). 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 20 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.

Limitations: 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 [10].

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 [10].

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 [2]. Energy consumption for copper recycling is 20% of production (13% in Energy

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& Recycling [4], 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 [10].

Disposal, polyethylene terephthalate, 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, land filing 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.

## 3. Life Cycle Interpretation

### 3.1 Results

The results were made using the

The environmental impact categories have been analyzed using two methods:

- Characterization,
- Normalization.

It has to be said, however, that only the first one – characterization - is obligatory in such analysis. This is due to the fact that there are many possibilities of normalizing results, many sets for those purposes are available and the final output is dependent on which set we use. In our analysis we have implemented the method Eco-indicator 99 (H) v2.3 with the normalization set of Europe EI 99 H/H. Eco-indicator 99 method, hierarchist version. Evaluation: "H" refers to the weighting set belonging to the hierarchist perspective [6].

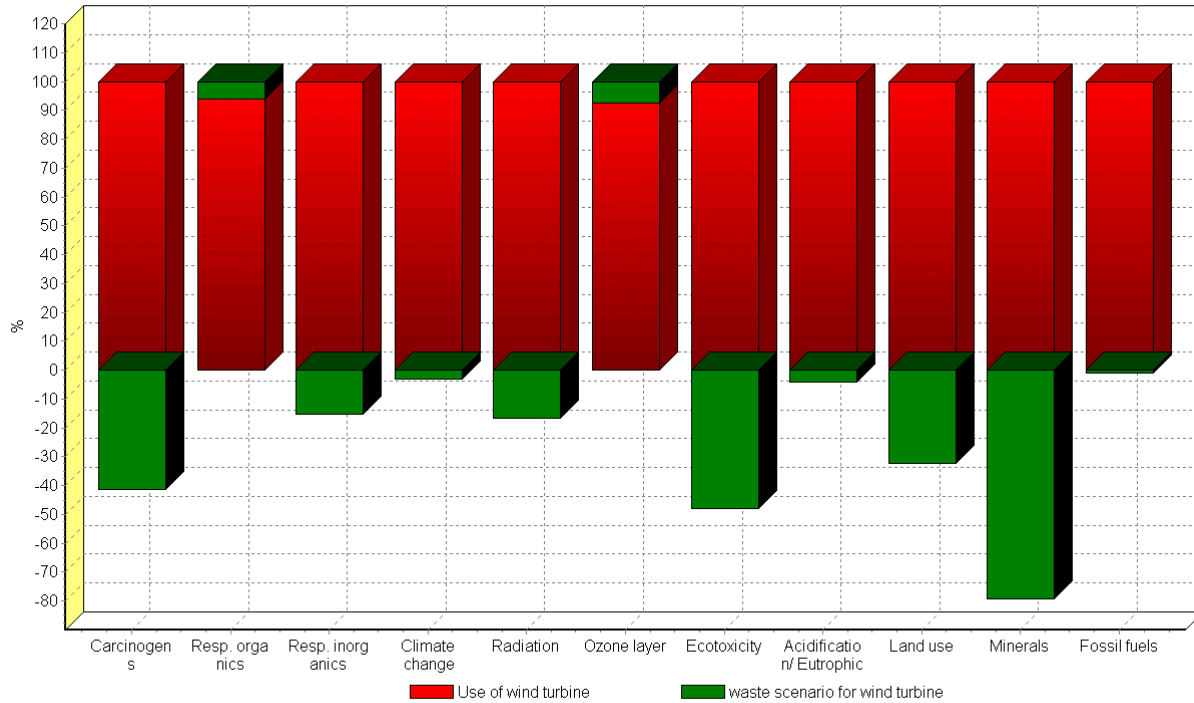
There are three kinds of units in which categories are presented [6]:

- DALY= Disability Adjusted Life Years; this means different disability caused by diseases are weighted;
- PDF\*m2yr; PDF= Potentially Disappeared Fraction of plant species;
- MJ surplus energy Additional energy requirement to compensate lower future ore grade.

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### 3.1.1 Characterization

This method shows how the waste scenario influences the impact of the use of the wind turbine and in what quantities. Red bars(darker colored bars) in Figure 4 represent the impact of the wind turbine without waste scenario, while the green bars show both how much of the impacts are increased by implementing the waste scenario (below 0% value) or their share in the negative impacts of the wind turbine.



**Figure 4. Characterization of the environmental impact assessment categories of wind turbine life cycle.**

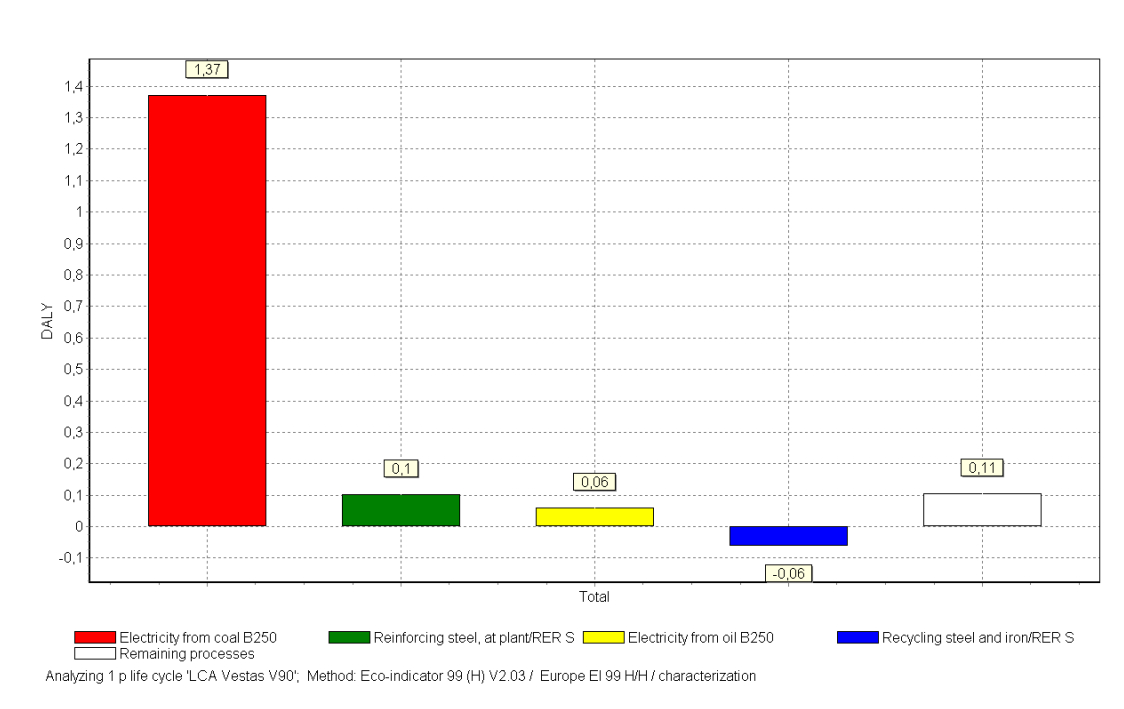
Additional graphs are presented for 4 categories (climate change, carcinogens, respiratory inorganic, fossil fuels) which have the biggest contribution in the total environmental impacts (see Figure 9).

#### Climate change

The electricity consumed during the manufacture of wind turbine is the largest contributor to the climate change (Figure 5 and Figure 6) with 85% out of total 1.58 DALY. This is because the power generation in Denmark is mainly based on coal (76% of Danish electricity in project BUWAL250 of SimaPro, 46% in Energy Statistics 2004 [3]), 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.

## Life Cycle Assessment for Wind Turbine



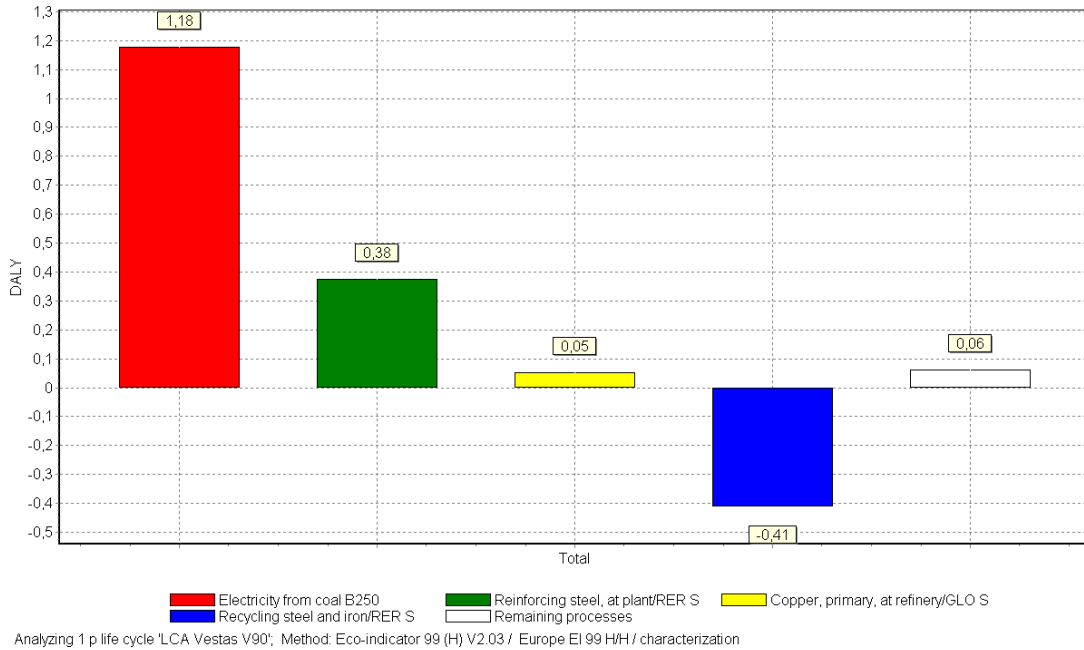
**Figure 5. Contributors to climate change potential (cut-off value 2%)**

### Carcinogens

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 4). Electricity from coal contributes most to the carcinogenic effect, followed by steel production and copper production (Figure 6). 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).

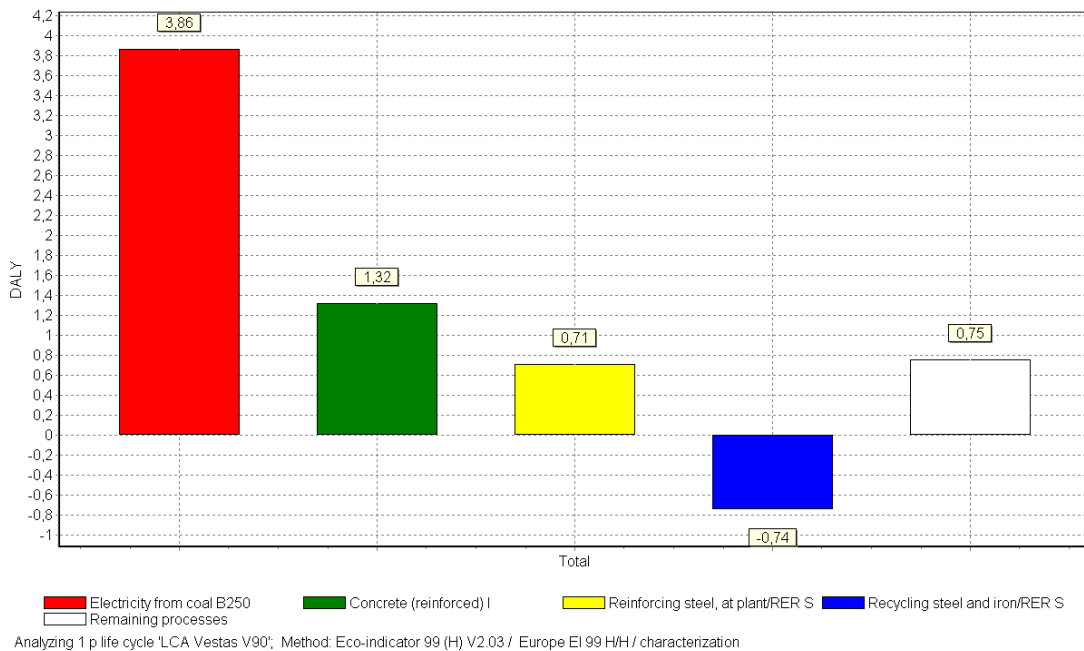
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**Figure 6. Contributors to carcinogens potential (cut-off value 4%)**

### Respiratory inorganics

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.

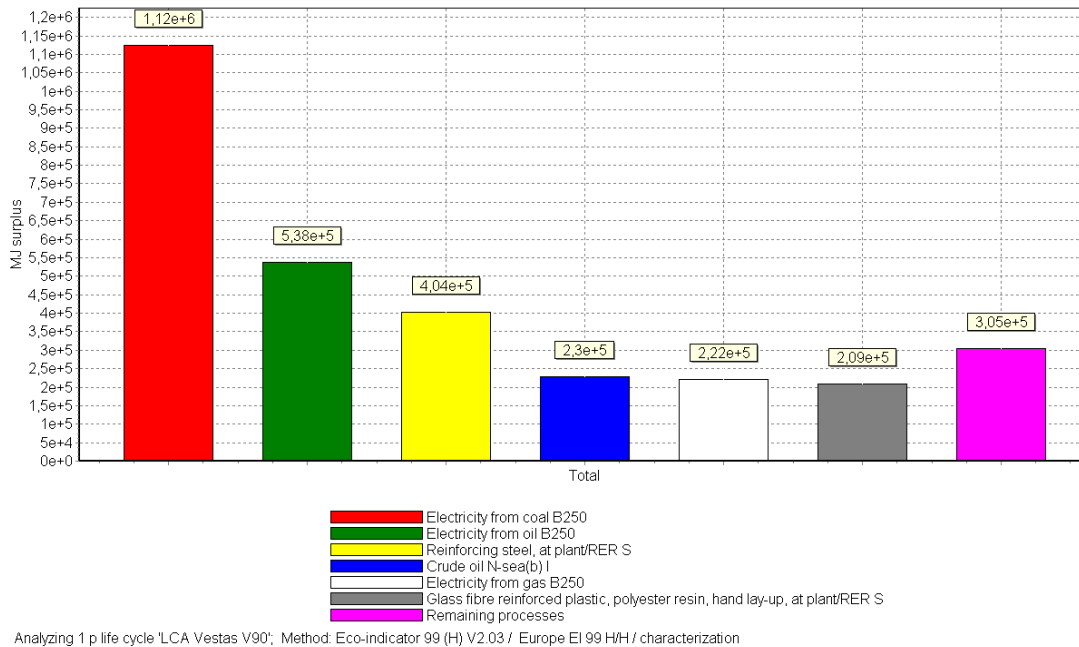


**Figure 7. Contributors to respiratory inorganics potential (cut-off value 4%)**

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### Fossil fuels

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 8 as crude oil.



**Figure 8. Consumptions of fossil fuels (cut-off value 4%)**

### 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  $7,45E-4$ .

### Radiation

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.

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### 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\*m2yr 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\*m2yr 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\*m2yr. 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.

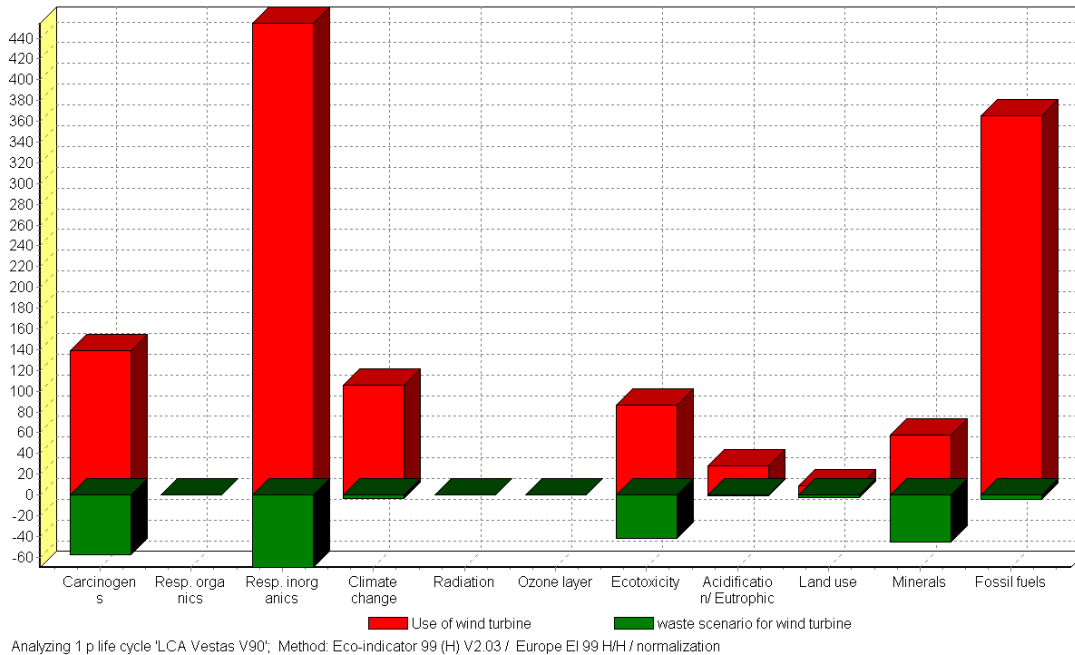
As we can see the waste scenario has different impacts in each category, of which three can be marked out as the most influenced ones: Mineral, Ecotoxicity and Carcinogens. It is caused by the fact that almost 80% of wastes (excluding concrete) were recycled. That allowed reusing received minerals, mainly 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.

### **3.1.2. Normalization**

This method helps the analyst to compare results of all impact categories by reducing them to a common unit called the reference (or normal) value. In SimaPro this is made by multiplying the category impact by the reference, which is in this case the average yearly environmental load in a country or continent, divided by the number of inhabitants. The lowest score category is being assigned the minimal value and the others respectively higher ones. In the analysis the Eco-indicator 99 (H) v2.3 method with the normalization set of Europe EI 99 H/H has been implemented, the damage categories are normalized on an European level (damage caused by 1 European per year), mostly based on 1993 as base year, with some updates for the most important emissions [6].

## Life Cycle Assessment for Wind Turbine



**Figure 9. Normalization of the environmental impact assessment categories of wind turbine life cycle.**

The Figure 9 shows the environmental load of the impact categories which were 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.

The normalization justifies our choice of climate change, carcinogens, respiratory inorganics and fossil fuels as main characterization categories. They have more significant impacts than the rest of categories.

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### 3.1.3. Results of different life cycle stages

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.

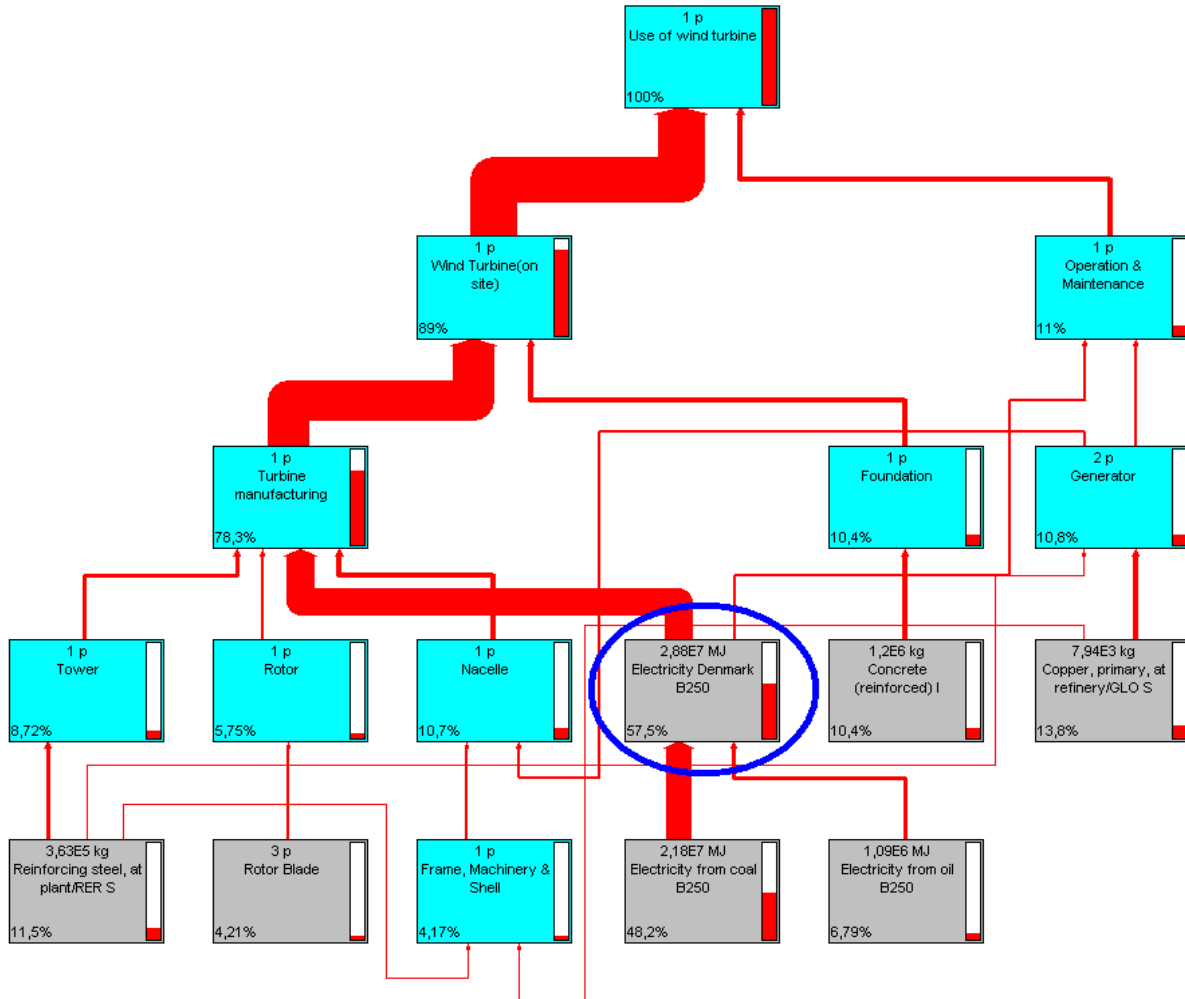


Figure 10. Flow chart of the ‘Use of the wind turbine’ with cut-off value of 4%.

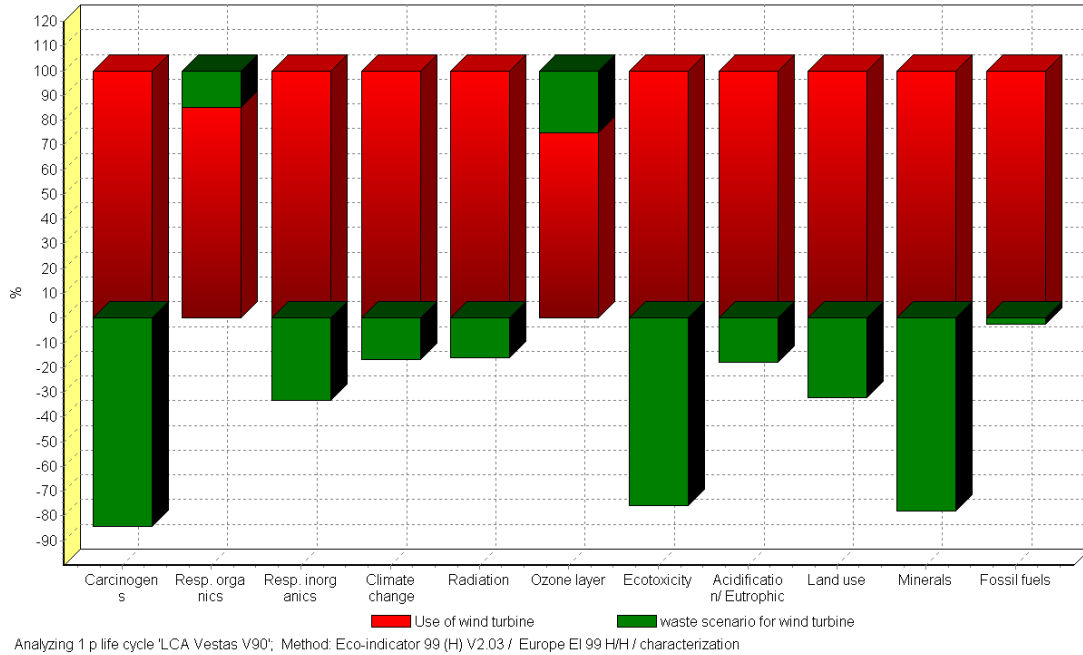
Having examined the chart, it was observed that energy consumption (especially from coal) expressed as electricity Denmark B250 has a major impact on environment (57.5%). It can be explained by its affecting the fuels consumption and thus resources mining as well as emission increase (greenhouse gasses,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

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%.



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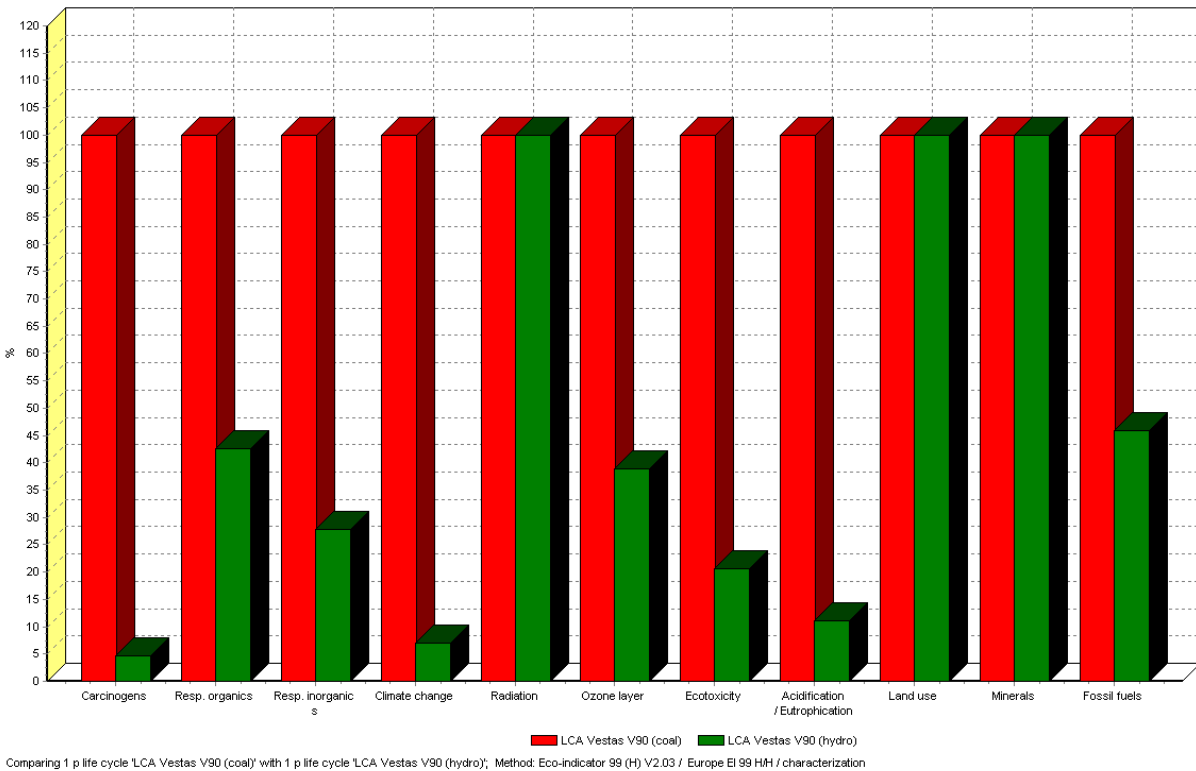


**Figure 12. Characterization of the environmental impact assessment categories of wind turbine life cycle with hydro power as the energy source.**

Due to the energy source change, the green bars have become longer. It could suggest that the waste scenario has been improved and reduces the negative impact more than previously. In fact, the waste scenario has not been changed at all and that illustrates the improvement of the use phase process.

But to receive a clear comparison of the two options the graph showing two characterization results was made (Figure 13).

## Life Cycle Assessment for Wind Turbine

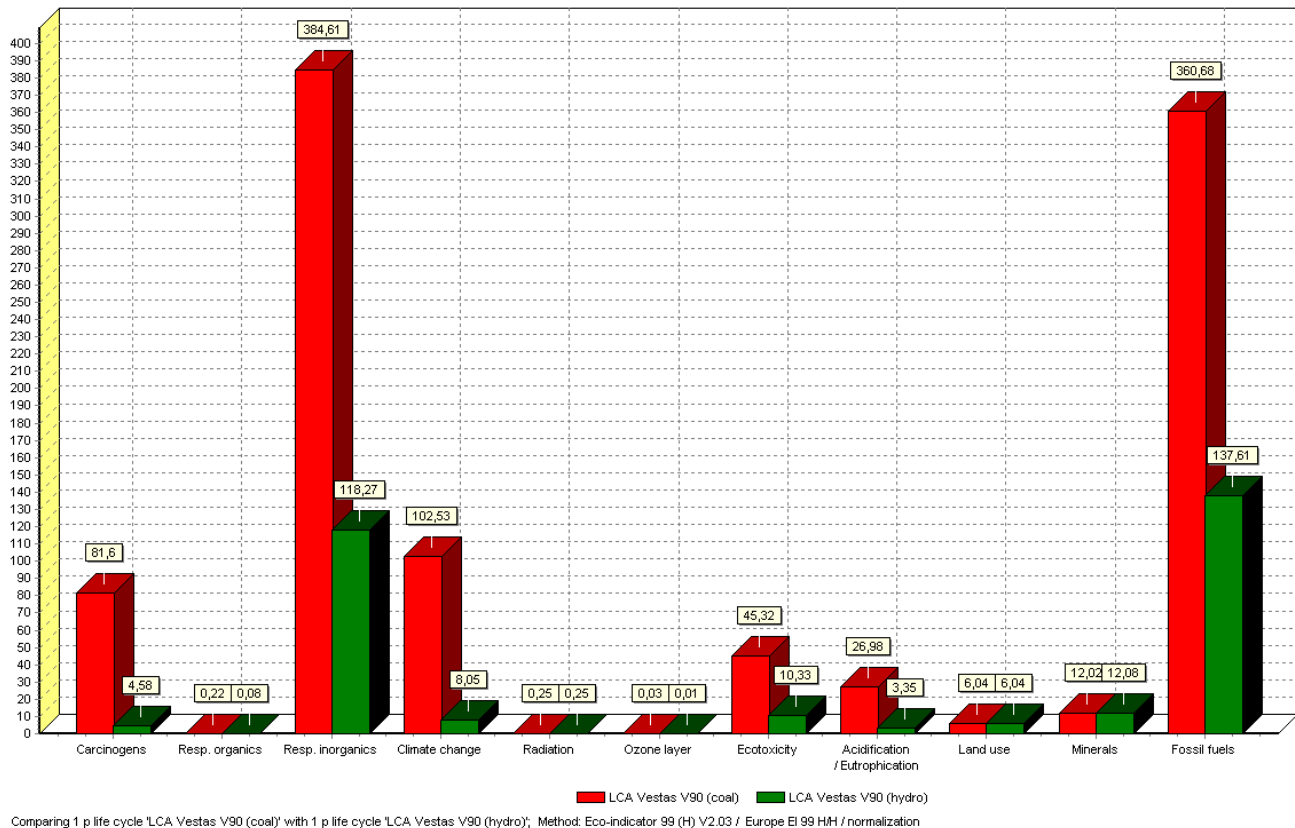


**Figure 13. Comparison of the environmental impacts caused by the wind turbines using different energy sources (coal and hydro) made with the characterization method.**

Implementing the new energy source causes a significant decrease of the negative impacts in 8 of 11 categories. The ones which should be pointed out are Carcinogens, Climate change and Acidification/ Eutrophication in which reduction amounted from around 90 to 95%. The negative impacts on Fossil fuels consumption have also been significantly lessened by over 50%. The change has not influenced the Radiation, Land use and Minerals consumption.

The normalized comparison graph presented below (Figure 14), shows instead the amount reduction:

## Life Cycle Assessment for Wind Turbine



**Figure 14. Comparison of the environmental impacts caused by the wind turbines using different energy sources (coal and hydro) made with the normalization method.**

The most meaningful reduction can be seen for respiratory inorganics emissions and fossil fuels consumption and amounts 266,3 and 223,1 points respectively. What is more, it is this second category which paradoxically, has the highest negative impact is on fossils, what can be explained by a large respiratory inorganics emission decrease.

### Energy source comparison

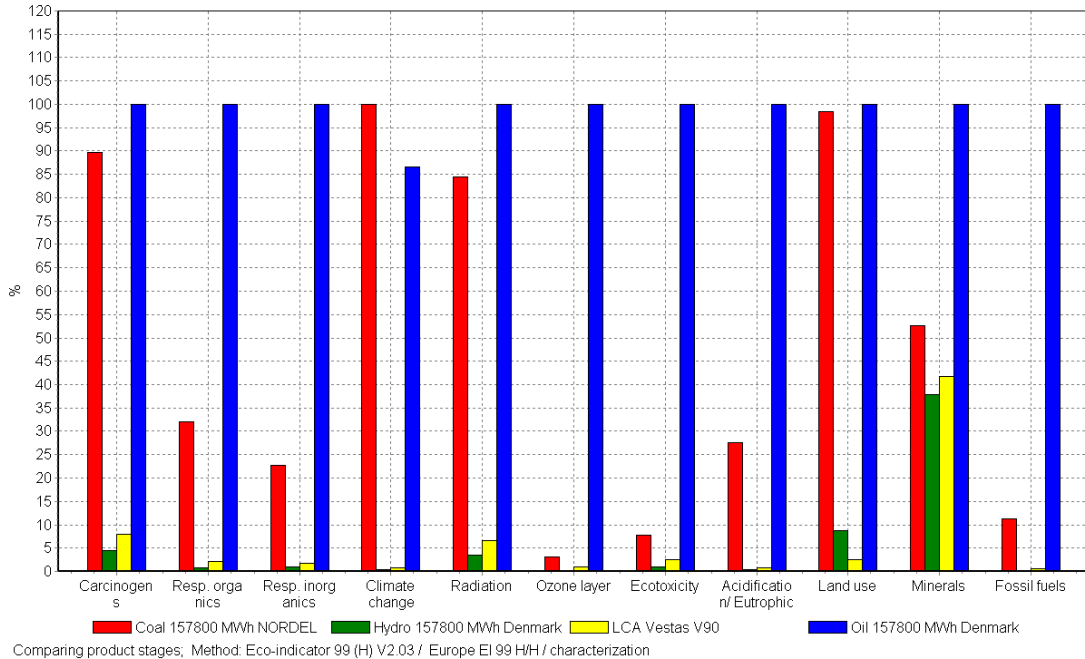
As the final task, impacts of the different-energy-source power plants were compared [6]:

- a coal power plant - Strom, ab Steinkohlekraftwerk,
- a hydro power plant - Strom, Wasserkraft, ab Kraftwerk,
- a wind power plant (on which this LCA is based),
- an oil power plant - Strom, ab Ölkraftwerk.

To make the comparison compatible the functional unit of 157,800 MWh was selected, which refers to the energy produced during the whole life time of the wind turbine.

The results are shown in the image below (Figure 15).

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**Figure 15. Comparison of impacts from different energy sources**

Energy production from the oil power plant showed to have the biggest negative impact on the environment. It is followed by coal with slightly smaller impacts and then by wind and hydro power plant, which have very minor impacts in relation to the first two ones. The only environmental category which is significantly affected by all energy sources is the Minerals category.

### System efficiency

As all impacts have been presented, the efficiency of the whole system was calculated, dividing the total energy output over the life time of the wind turbine (which is what is being generated during 20 years) and by the total energy input over the life time of wind turbine (which is what is being consumed during 20 years). The following data have been used:

- the total energy input over the life time = 7795 MWh (see section 2.2.2)
- the total energy output over the life time = 157800 MWh (see section 1.2)

$$\eta = 157800 / 7795 = 20,24 ,$$

where  $\eta$  is the efficiency.

It means that the amount of energy generated is 20,24 times bigger than energy consumed over the life time, what presents the wind energy as an efficient one and energy-profitable.

## Life Cycle Assessment for Wind Turbine

### 3.2 Conclusions and recommendations

The goal of assessing the life cycle of wind turbines has been fully achieved through this study. We analyzed the entire life cycle starting from 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 the Denmark 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 from Norway was selected as the source of electricity to manufacture the wind turbine, the negative impacts on the environment were 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 undoubtedly regarded as the next step to achieving the sustainable development.

## Life Cycle Assessment for Wind Turbine

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