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Life cycle assessment of the offshore wind farm *alpha ventus*

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ABSTRACT

Due to better wind conditions at sea, offshore wind farms have the advantage of higher electricity production compared to onshore and inland wind farms. In contrast, a greater material input, leading to increased energy consumptions and emissions during the production phase, is required to build offshore wind farms. These contrary effects are investigated for the first German offshore wind farm *alpha ventus* in the North Sea. In a life cycle assessment its environmental influence is compared to that of Germany's electricity mix.

In comparison to the mix, *alpha ventus* had better indicators in nearly every investigated impact category. One kilowatt-hour electricity, generated by the wind farm, was burdened with 0.137 kWh Primary Energy-Equivalent and 32 g CO_2-Equivalent, which represented only a small proportion of the accordant values for the mix. Furthermore, the offshore foundations as well as the submarine cable were the main energy intensive components. The energetic and greenhouse gas payback period was less than one year.

Therefore, offshore wind power, even in deep water, is compatible with the switch to sustainable electricity production relying on renewable energies. Additional research, taking backup power plants as well as increasingly required energy storage systems into account, will allow further calculation.

1. Study focus and investigated wind farm

Due to better offshore wind conditions, offshore wind farms have the advantage of a higher electricity production in comparison to onshore and inland wind energy converters. Hence, higher full load hours can be reached. In contrast, there is an increased input of material and energy to build up the offshore wind farm. This effect is mainly based on additional components, like the complex foundations of the wind energy converters and offshore transformer stations as well as the submarine cables. Larger distances for maintenance and more complex maintenance procedures lead to the same effect.

The object of investigation is the first German offshore wind farm *alpha ventus* beyond the territorial waters (twelve mile zone) in the German exclusive economic zone. *Alpha ventus* is a test field in the North Sea for 5 MW wind energy converters in a water depth of 30 m. The field consists of six converters of the type 5M (manufacturer REpower) that are installed on Jacket foundations and six converters of the type M5000 (manufacturer Multibrid) that are built on Tripod foundations. All converters are connected by a 16 km submarine cable at 30 kV. An offshore transformer station steps up the voltage for the 110 kV submarine cable. The electricity is transported over 60 km to an onshore transformer station, which supplies the German high-voltage grid.

This study focuses on a life cycle assessment of *alpha ventus*. Several indicators are taken into consideration and investigate the resource conserving and environmentally friendly way of power generation in comparison to the German grid mix.

2. Methodological approach

The different steps of a life cycle assessment (LCA) are defined in the international standards DIN EN ISO 14040 [1] and DIN EN ISO 14044 [2]. This study is orientated toward these standards, which structure the analysis as follows:

The **Goal and Scope Definition** includes the description of the balance object, the system boundaries and the assumptions made. In this study the functional unit was defined as the supply with 1 kW-hour current generated by alpha ventus at the high-voltage grid at the onshore transformer station in Hagermarsch (Germany). During the **Inventory Analysis** all material, energy and emission flows (input and outputs) are investigated and lead to the life cycle inventory analysis result. Within the **Impact Assessment**, the impact categories as well as their indicators are defined. The inputs

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Nomenclature

AP	acidification potential
CED	cumulated (Primary) energy demand
CED_P	CED of the production phase
CED_U	CED of the use phase
$CED_{U,y}$	yearly CED of the use phase
CED_D	CED of the disposal phase
$E_{el,y}$	yearly generated electric energy
EP	eutrophication potential
Eq.	equivalent
g	supply factor
GWP	global warming potential
HTP	human toxicity potential
IOA	energetic input output analysis
LCA	life cycle assessment
MBA	material balance analysis
PCA	process chain analysis
PE	primary energy
POCP	photochemical ozone creation potential
WEC	wind energy converter

and outputs are classified by these impact categories. Using characterization factors, the impact category indicators are calculated. Finally, in the **Interpretation** step, the results of the life cycle assessment are evaluated to reach conclusions. Additionally, an optional sensitivity analysis investigates responsive parameters and their influence on the results.

Three different methodological approaches exist to calculate the above mentioned indicators: the energetic input output analysis (IOA), the process chain analysis (PCA) and the material balance analysis (MBA). Due to the potential of receiving inaccurate results performed by an IOA and the dependence on detailed process data for a PCA and its extremely time consuming balance process, these balancing methodologies were left out. An ideal compromise between a high accuracy of the result and an acceptable expenditure of time can be reached by the performed MBA. Another advantage is that data concerning mass, material and type of production are sufficient to calculate the indicators. The approach was structured as follows:

In the first step, the inventory – in this case all the component parts and structural elements of the wind farm – was listed. In the second step, the inventory analysis result for the manufacturing phase, the use phase, as well as the disposal phase was built. The main part of the **production phase** was the calculation of the raw material and their respective masses (under consideration of common proportions of recycled material) and the subsequent processes. Additionally, the transport of the components between the different production facilities and to the building site was included, as well as the assembling of the components (wind energy converters, transformer stations and submarine cables). In conjunction with the operating company, the maintenance and maintenance assignments for the **use phase** for each wind energy converter were assumed (Table 1). Part of the **disposal phase** was the dismantling and the return transports of the structural elements. The inventory analysis result was built in cooperation with respective manufacturers and the operator of the wind farm. Due to non-disclosure agreements with respective manufacturers, the contemporary publication of detailed datasets of their products has to be avoided. Previous calculations [3], own investigations as well as assumptions on basis of corresponding literature helped to fill gaps with data. In the third step, specific energy expenditures

Table 1
Overview of the scenarios – changes compared to the standard scenario (A) are marked.

Scenario	Description	Technical Lifetime[a]	Full Load Hours[b]	Maintenance Assignment[c]	Number of WEC[c]
A	Standard Scenario	Foundation and Sub. Cable 20 years	3900 h/a	10 Helicopter and 15 Shipping Services per year and WEC	12
B	Foundation and Sub. Cable 40 years	Foundation and Sub. Cable 40 years	3900 h/a	10 Helicopter and 15 Shipping Services per year and WEC	12
C	Full Load Hours 3600	Foundation and Sub. Cable 20 years	3600 h/a	10 Helicopter and 15 Shipping Services per year and WEC	12
D	Full Load Hours 4200	Foundation and Sub. Cable 20 years	4200 h/a	10 Helicopter and 15 Shipping Services per year and WEC	12
E	Half Maintenance Assignment	Foundation and Sub. Cable 20 years	3900 h/a	5 Helicopter and 7.5 Shipping Services per year and WEC	12
F	Wind Farm *beta ventus*[d]	Foundation and Sub. Cable 20 years	3900 h/a	10 Helicopter and 15 Shipping Services per year and WEC	40

[a] The technical lifetime of the other components of the wind farm is 20 years.
[b] Including down time and losses during transmission to onshore transformer station.
[c] Maintenance for each wind energy converter (WEC) over the technical lifetime for every scenario: replacement of 0.5 gear boxes and 1.25 rotor blades.
[d] Assumption for the fictitious wind farm *beta ventus* (40 WEC): same transformer stations and submarine cable like wind farm *alpha ventus*.

and produced emissions were linked to the inventory analysis result. The database of the Swiss Center for Life Cycle Inventories *Ecoinvent* [4] lists over 4000 datasets for specific energy expenditures and produced emissions for raw material. Furthermore, data for subsequent processing, like forging or welding, can be withdrawn. With the help of the balancing software *GaBi* [5] and the implemented *Ecoinvent* database, the linking process could be performed and the offshore wind farm analyzed holistically.

2.1. Cumulated energy demand

As the routing indicator the cumulated (primary) energy demand (CED) was chosen, which sums up every energetic input over the life cycle of a product evaluated on a primary energy basis. It is measured in TJ primary energy-equivalent (PE-Eq.). The CED has to be expended to create the utilizable product, or in this case, useful energy (electricity) generated by the offshore wind farm. It allows an energetic comparison to other power generating systems and their respective CED. Corresponding to the technical standard VDI 4600 [6], the CED is defined as "the entire demand, valued as primary energy, which arises in connection with the production (CED_P), use (CED_U) and disposal (CED_D) of an economic good (product or service) or which may be attributed respectively to it in a causal relation". Thus, the CED is the sum of the CEDs of the different life cycle phases (Equation 1):

$$CED = CED_P + CED_U + CED_D \quad (1)$$

2.2. Global warming potential

Due to the current public focus on the reduction of greenhouse gases, the global warming potential or greenhouse warming potential (GWP) cumulates every carbon dioxide equivalent emission. Hence, it describes the anthropogenic global warming effect, which leads to the increase of the global average temperature. The GWP is measured in kg CO_2-Equivalent and is defined as the increase of the radiative forcing caused by the adsorbed infrared radiation of atmospheric trace gases, which is a result of the increased concentration of atmospheric greenhouse gases [7].

2.3. Additional indicators

In this LCA further indicators, such as the eutrophication potential (EP), the human toxicity potential (HTP), the photochemical ozone creation potential (POCP) and the acidification potential (AP), were investigated. In this context, the EP (measured in kg PO_4^{3-}-Equivalent) indicates emissions leading to an over-fertilization of ground and waterbodies and the HTP (measured in kg DCB-Equivalent) the influence of toxic emissions on humans. Furthermore, the POCP (measured in kg C_2H_4-Equivalent) displays emissions which cause ozone-smog and the AP (measured in kg SO_2-Equivalent) announces acidic emissions into the air leading to acid rain.

2.4. Energetic and greenhouse gas payback period

The energetic payback period is an important key figure to determine the sustainability of power plants using renewable energies. It describes the time frame to compensate the energetic expenses, valued as primary energy, for the entire life cycle of the power plant. In this case, the offshore wind farm generates electricity without any additional energetic input to compensate the energetic expenses for production, use and disposal. To value the generated electricity as primary energy, German's electricity mix was chosen as the comparing system. The gross power generation 2009 in Germany respecting different energy sources consists of 43% coal, 23% nuclear power, 13% natural gas and 16% renewable energy. The energetic supply factor g for Germany is about 3.0 kWh Primary Energy-Equivalent per kWh electricity (see also Table 2) [4]. The calculations are based on the computational method of VDI 4661 [8] (Equation 2). This methodological approach assumes that the yearly energy expenditure for the use phase ($CED_{U,y}$) is covered by the yearly generated electricity ($E_{el,y}$) valued as primary energy.

$$\text{Energetic payback period} = \frac{CED_P + CED_D}{E_{el,y} \cdot g - CED_{U,y}} \qquad (2)$$

Table 2
Energetic and greenhouse gas payback period (definition of the scenarios in Table 1).

Scenario	Description	Generated Electricity[a] over 20 years	Energetic Payback Period[b]	Greenhouse Gas Payback Period[c]
A	Standard Scenario	4680 GWh	8.8 Month	9.1 Month
B	Foundation and Sub. Cable 40 years	4680 GWh	6.1 Month	6.3 Month
C	Full Load Hours 3600	4320 GWh	9.5 Month	9.9 Month
D	Full Load Hours 4200	5040 GWh	8.1 Month	8.5 Month
E	Half Maintenance Assignment	4680 GWh	8.7 Month	9.1 Month
F	Wind Farm *beta ventus*[d]	15,600 GWh	7.4 Month	7.7 Month

[a] Unweighted = secondary energy.
[b] Energetic supply factor for the German electricity mix at the high-voltage grid: 3.007 kWh PE-Eq./kWh_{el} [4].
[c] Greenhouse gas supply factor for the German electricity mix at the high-voltage grid: 0.665 kg CO_2-Eq./kWh_{el} [4].
[d] Assumption for the fictitious wind farm *beta ventus*: same transformer stations and submarine cable like wind farm *alpha ventus*.

To investigate the influence on the climate change, the greenhouse gas payback period was calculated, too. This key figure describes the time for the compensation of the carbon dioxide equivalent emissions during the entire life cycle. As the comparing system, the German electricity mix was chosen, as well. Table 2 shows the assumed greenhouse gas supply factor. To calculate the greenhouse gas payback period, each CED in Equation 2 has to be replaced by the respective GWP. Likewise, the supply factor has to be adjusted.

2.5. Input data quality

Concerning the input data for material and masses, the preliminary work for the study led to a satisfying inventory analysis result. Detailed information of manufacturing companies and own databases from previous studies were taken into consideration. Due to the high proportion of the ferrous metals and hence high influence on the results, the importance was attached to the accuracy of the data concerning these materials. The data insecurity of the specific CED and GWP values is estimated at about 10%. The databases used for specific CED and GWP along with other investigated indicators are trustworthy, up to date and published by acknowledged research institutes. Generally speaking, all assumptions for the study have been made to a rather pessimistic point of view, to be sure to calculate the worst case and its most extensive environmental influence.

3. Results and discussion

The results are organized to give an overview of the CED, itemized with respect to the life cycle phases of the wind farm in the standard scenario. Table 1 shows all assumptions concerning this scenario with respect to the technical lifetime of the foundation and the submarine cable, the full load hours, the maintenance and the maintenance assignments. Additional scenarios are investigated afterward to show sensitive input data. Therein changed parameters are described later on. Moreover, the energetic and greenhouse gas payback period is displayed. In a final step, the CED and GWP as well as the additional indicators EP, HTP, POCP and AP are taken into account and compared to the results of the German electricity mix.

For the wind farm, Fig. 1 displays the total material balance itemizing different substances. All together about 29,000 tons of material are installed. Of major significance is the proportion of the ferrous metal (73.2%). Especially the foundations of the offshore installations, which contribute more than half of the ferrous metal,

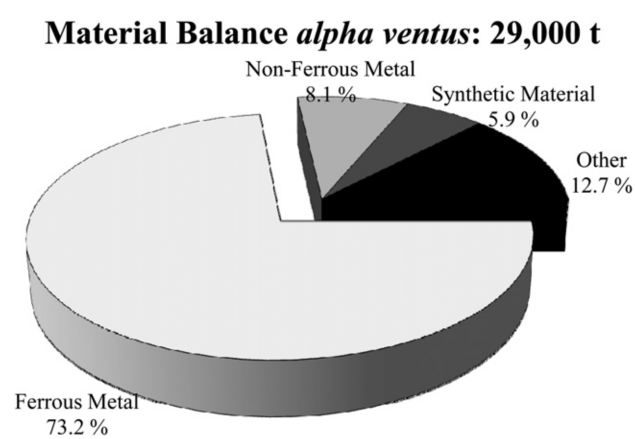

Fig. 1. Material balance of the wind farm *alpha ventus* (including the grid connection).

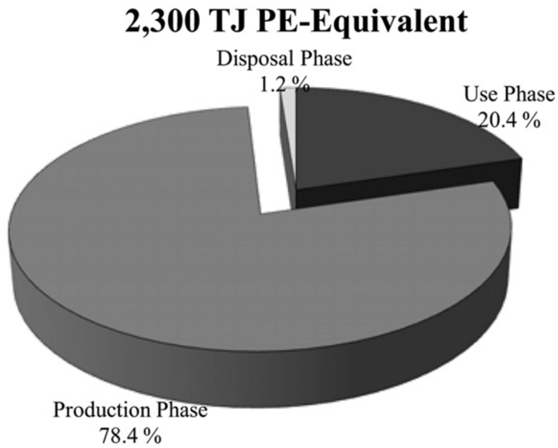

Fig. 2. CED of the wind farm *alpha ventus* (standard scenario) itemized respecting life cycle phases.

have a considerable influence. Non-ferrous metal has a proportion of 8.1%. In the first approximation, the submarine cable adds up to 80% of the non-ferrous metal.

3.1. CED and GWP results respecting the life cycle phases

In total, about 2300 TJ PE-Equivalent have to be expended for the entire life cycle of *alpha ventus* in the standard scenario (Fig. 2). A proportion of nearly 80% is attributed to the production phase, followed by the use phase (about 20%). The disposal phase contains the deconstruction and has a minor influence compared to the other life cycle phases. Subsequently, the GWP results and more detailed CED results of the production and use phase are described.

Concerning the GWP, about 149,000 t CO_2-Equivalent are expended for the entire life cycle of *alpha ventus*. The proportions of the different life cycle phases nearly equal the respective one of the CED (Fig. 2). This is on account of the high proportion of the CO_2 emissions (about 90%) in the GWP, which are mainly caused by the expenditure of fossil energy. Thus, they are related to the CED. From now on, the paper focuses on the CED, because the GWP shows a corresponding behavior and provides no additional conclusions.

3.1.1. Production phase

Fig. 3 gives an overview of the production phase and the contribution of the different structural components to the total CED. The main influence of a single component has the 110 kV submarine cable. Its production contributes about 12% to the total CED. Due to the tremendous impact of the submarine cable, the distance between the wind farm and the shore is of major importance, as well. The offshore and onshore transformer stations sum up to 6%. Regarding the components of the twelve complete wind energy converter units, they consist of the wind energy converter (Multibrid M5000 or REpower 5M), the foundation (Jacket or Tripod) and the proportionate 30 kV submarine cable. Each converter contributes with about 2%. Considering this, the six Multibrid M5000 converters as well as the six REpower 5M converters have roughly the same amount as the 110 kV submarine cable. Another major energy consuming factor is the foundation. All twelve foundations add up to an amount of 35% to the total CED. In comparison, six Tripod foundations contribute about 3 percentage points more to the total CED than six Jacket foundations. The reason for this difference is the steel consumption of the Tripod. Each Tripod contains about 200 t more steel than the Jacket foundation. The 30 kV submarine cable has a lower influence, because of the small distances within the wind farm (16 km in total), compared to 65 km of the 110 kV submarine cable.

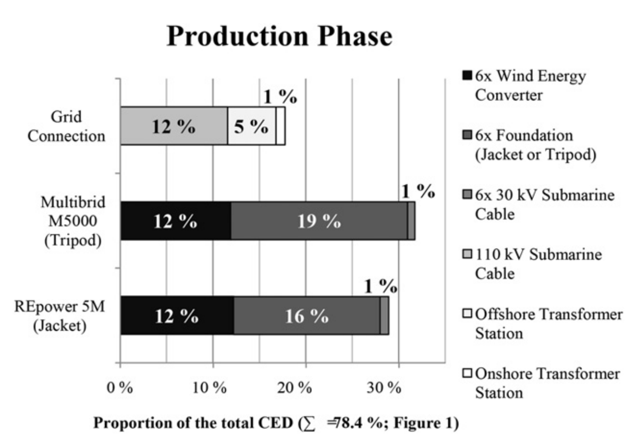

Fig. 3. Proportion of the production phase of the wind farm *alpha ventus* to the total CED (standard scenario).

3.1.2. Use phase

Investigating the use phase, the calculations show that about 70% of the 470 TJ PE-Equivalent for the use phase (Fig. 2) are expended for shipping services (Table 1). Another 12% are expended for transports by helicopters. Changing gear boxes, blades and oil as well as the transport and assembling of the spare parts have a proportion of about 18% altogether.

3.2. Sensitivity analysis

During the sensitivity analysis, basic parameters were varied to investigate their influence on the total CED (Table 1). Scenario A characterizes the standard scenario. The previous section pointed out the tremendous influence of the submarine cable and the foundations. Hence, their technical lifetime was increased from 20 to 40 years in scenario B. Concerning the uncertainty of the fluctuating wind supply, the internal electric losses and the own consumption, the full load hours were varied. To quantify the influence, the value was diversified from 3900 h/a to 3600 h/a (scenario C) and 4200 h/a (scenario D). Because of the missing experience concerning the maintenance assignment for offshore wind farms, their ample assumptions were halved in scenario E. In a long-term view the maintenance assignments will be standardized and benefit from synergetic effects in a commercial offshore wind energy sector. To investigate possible scale effects of projected commercial wind farms, the number of the wind energy converters was changed from 12 to 40 in scenario F.

Fig. 4 shows the CED per generated kilowatt-hour electricity of the different scenarios. The standard scenario has a value of 0.137 kWh PE-Eq./kWh_{el}. In comparison, the energetic supply factor for the German electricity mix at the high-voltage grid mounts up to a tremendously higher value of 3.007 kWh PE-Eq./kWh_{el} [4]. Changing the technical lifetime (scenario B) has a major influence on the specific CED. Here, the value decreases to 0.103 kWh PE-Eq./kWh_{el} (reduction of about 25%). Therefore, the submarine cable and the foundations enable a great potential for further improvement and a decrease of the CED up to 25%, if it is possible to improve these construction elements. Comparing scenarios A, C and D, varying the full load hours show an approximately linear effect on the specific CED. Cutting the maintenance assignments in half lowers the specific CED to 0.125 kWh PE-Eq./kWh_{el}. To use this potential to lower the CED up to 9%, standardization should be implemented and synergetic effects should be occupied. Scenario F shows a decrease of the specific CED of about 12% for the fictitious

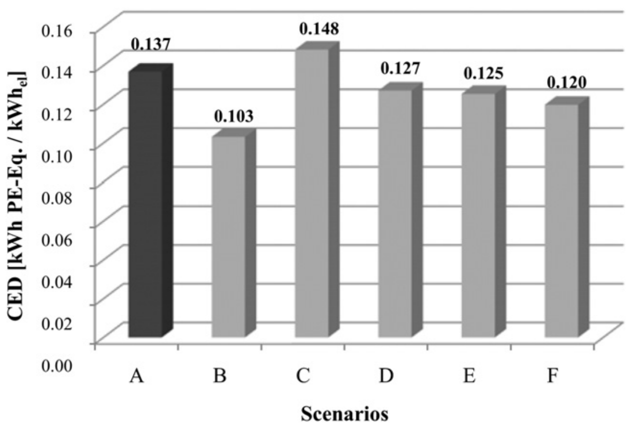

Fig. 4. CED per kilowatt-hour electricity itemized respecting the different scenarios (definition of the scenarios in Table 1).

wind farm *beta ventus*. Assumed are the same transformer stations and submarine cable as installed in the wind farm *alpha ventus*, because of the absence of reliable data until now. This assumption has to be verified for projected commercial wind farms. If these components, especially the submarine cable, have to be modulated, this may result in an intense expense of energy and a rise of the specific CED. The advantage of the fictitious wind farm *beta ventus* may even up.

3.3. Payback periods

Concerning the payback periods, Table 2 shows the results for the different scenarios. For any scenario, the energetic input for the wind farm is amortized after less than 10 months. Regarding the results for the different scenarios, the change of the parameters show the above described effect (for the specific CED) here for the energetic payback period.

The greenhouse gas payback period is about a half month longer than the energetic payback period for the respective scenario (Table 2). The results show a strong correlation between each other. Due to the effect that the CO_2 emissions are mainly based on the energetic expenditures, the high proportion of about 90% of the CO_2 emissions in the emitted greenhouse gases lead to this correlation. Therefore, within less than one year the energetic expenditure as well as the greenhouse gas emission of the entire life cycle of *alpha ventus* is amortized.

3.4. Additional indicators and comparison to German grid mix

Besides the energy consumption (CED) and the influence on the climate (GWP), there are additional indicators to investigate the environmental influence. Fig. 5 shows the specific results of the additional indicators for *alpha ventus* in comparison to the German electricity mix. Backup power plants for time of weak winds are not considered. The maximum of both values per category represents the maximum of the respective axis. Hence, every indicator has the same importance and there is no weighting between the indicators. This is an appropriate approach for the scientific discussion of results. For political consulting discussions it can be appropriate to consider normalized and weighted results, which are published in the comprehensive study [9]. The area spread for *alpha ventus* (dark) is significantly smaller than the area spread for the German electricity mix (light). Thus, *alpha ventus* is the better way to generate electricity concerning the investigated indicators.

In detail, especially the already discussed indicators CED and GWP have tremendous lower values for *alpha ventus* in comparison to the mix. The GWP for *alpha ventus* is 32 g CO_2-Equivalent per kWh electricity in comparison to 665 g CO_2-Equivalent per kWh for the mix [4]. Comparing different power generating systems, the wind energy represents one of the techniques with the lowest specific GWP. Solar thermal, nuclear and hydro power plants are in the same range [10]. Due to the high number of fossil and especially hard coal and lignite fired power plants in Germany, there are significant consumptions of fossil energy as well as emissions concerning carbon dioxide, nitrogen oxide and sulfur dioxide. This leads to high values for the mix in the categories AP, EP and POCP. In contrast, *alpha ventus* uses renewable energy and has therefore no direct emission or consumption of fossil energy in the use phase.

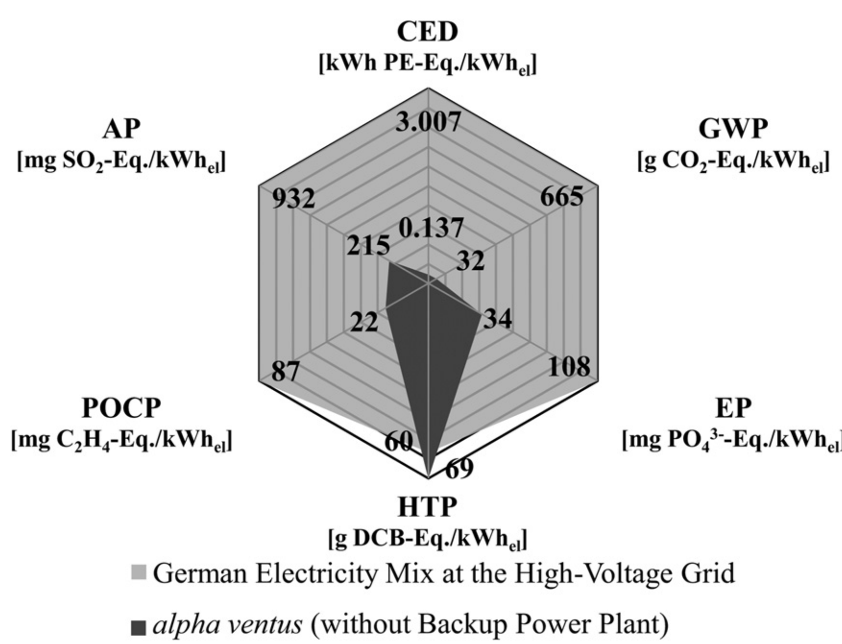

Fig. 5. Polar diagram for the comparison of the indicators of *alpha ventus* (standard scenario) and the German electricity mix [4].

Especially, the significant indicators for the power generating industry (GWP and AP) show the considerable advantage of the offshore wind energy, because electricity generated by *alpha ventus* is burdened with only a fraction of the value of the mix. The HTP is the only investigated indicator with a slightly higher value for *alpha ventus*. This can be explained by the higher rate of installed steel and especially copper per generated kilowatt-hour electricity in comparison to the mix, which is mainly based on conventional power plants with very high capacities. Especially the foundations and the submarine cable of *alpha ventus* play a decisive role. During the production of the respective raw materials in metallurgical plants heavy metal emissions occur in upstream processes, which lead to the high value for *alpha ventus* in this category. In addition, the HTP has an intrinsic and unavoidable uncertainty range [11], which puts the marginally difference into perspective.

4. Prospects

Electrical power generated by wind energy converters does not lead to assured electricity supply, because of fluctuating wind conditions. For a save supply in the mix during the time of weak winds backup power plants are necessary. They are not included in the calculations of this study. Nevertheless, a further extension of the offshore wind energy improves the environmentally friendliness and sustainability of the energy mix. Besides this, the switch leads to an increasing requirement for energy storage, such as pumped storage power plants or compressed air energy storage with an additional influence on the environment. In the future reliable data will allow further calculations of projected commercial wind farms.

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