

Article

Resource Use of Wind Farms in the German North Sea—The Example of Alpha Ventus and Bard Offshore I

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Abstract: The German government aims to obtain at least 40 percent of its electricity from renewable sources by 2030. One of the central steps to reach this target is the construction of deep sea offshore wind farms. The paper presents a material intensity analysis of the offshore wind farms “Alpha Ventus” and “Bard Offshore I” under consideration of the grid connection. An additional onshore scenario is considered for comparison. The results show that offshore wind farms have higher resource consumption than onshore farms. In general, and in respect to the resource use of other energy systems, both can be tagged as resource efficient.

Keywords: resource efficiency; resource use; material input per service (MIPS); wind energy; grid connection

1. Introduction

Considering the growing energy demand, environmental problems and rising prices of raw materials, higher resource efficiency in the energy sector is called for. As this paper will show, the use of renewable energies is one of the central steps to reduce the resource requirement of energy generation. Today, wind energy is the major German renewable energy source for electricity generation supplying about 46 TWh/a [1], which is expected to quadruple in 2030 [2]. At that time, about one half of the wind energy will be supplied by offshore wind farms [2]—most of them placed in

the deep sea [3]. Against this background the question arises, how resource efficient offshore wind farms are in contrast to onshore wind farms and the German energy system—especially when built far from the coast in deep water.

This paper analyses the life cycle wide resource use of two offshore wind farms in the German North Sea. The first wind farm, pioneer project “Alpha Ventus” (WFAV), is Germany’s first deep sea offshore farm. According to the eco balance in [4], its life cycle wide emissions are well below the German electricity mix. The second wind farm, “Bard Offshore 1” (WFBO1), will be the republic’s first commercial deep sea wind farm, scheduled to be fully operational by the beginning of 2014 and has, to the knowledge of the authors, not been subjected to a life cycle analysis before. Both wind farms are equipped with similar 5 MW wind turbines, but differ regarding their overall amount of turbines and their grid connection.

WFAV consists of six turbines type “Areva Multibrid M5000” and six turbines “Repower 5M”, both with a rated power of 5 MW. Since the Multibrid M5000 material inventories were not available, WFAV is accounted under the assumption of twelve “Repower 5M” turbines. The wind farm is connected to the inland high voltage grid by a 66 km long high-voltage rotating alternating current (HVAC) transmission. Further and more disseminated data on WFAV can be found in [4,5].

WFBO1 represents a 400 MW offshore wind farm with 80 turbines type “BARD 5.0” (5 MW), connected by a 200 km high-voltage direct current (HVDC) transmission (see [6] for more details). The paper on hand intends to illustrate the resource efficiency potentials of recent wind farm technologies and, in particular, their grid connection [4,5].

Also, an onshore scenario for the Repower 5M has been considered for comparison. Because the Repower 5M turbine is suitable for offshore and onshore use [7], only minor changes had to be made in the material inventory of nacelle and tower like the missing helipad and docking station [5]. As no wind farms with an amount of twelve 5 MW turbines could be identified by the authors for Germany, an onshore wind farm (WFON) with twelve Repower 5M turbines has been assumed. It’s connected via a 15 km HVAC connection to the inland high-voltage grid and is based on average wind speed data from a wind farm placed in the north-easterly of Germany [5]. In opposition to a real onshore wind farm, consisting of turbines in the power range of 2 to 3 MW, it is well suited for the analysis, because the generator power defines predominantly the weight and volume specifications of nacelle, tower and foundation. Table 1 outlines the data of the wind farms assessed in the analysis.

Table 1. Outline data of analyzed wind parks (table compiled by authors [5,6]).

Scenario	WFAV	WFBO1	WFON
Rated power	60 MW	400 MW	60 MW
Water depth	ca. 30 m	ca. 40 m	-
Middle full load hours (net)	3667 h/a	4250 h/a	2900 h/a
Energy yield (net)	220 GWh/a	1700 GWh/a	146 GWh/a
Blade diameter	126 m	122 m	126 m
Hub height	92 m over sea	90 m over sea	117 m over NN
Foundation	Jacket	Tripile	Spread
Grid connection	110 kV AC	150 kV DC	110 kV AC

2. Methodology

To measure the life cycle wide resource use, the method Material Input Per Service unit (MIPS) has been applied [8–10]. MIPS is an input oriented approach which allows to measure all natural resources taken from nature (material input) to provide a specific service or benefit to be defined by the service unit. In contrast to LCA methods there is no impact assessment, but as all emissions and related impacts result from the extraction of natural resources, a reduction of the inputs can also lead to a decrease of all emissions and environmental impacts.

The material inputs are divided in up to five resource categories, which are measured in kilograms or tons:

- Abiotic resources (e.g., minerals, and fossil fuels)
- Biotic resources (e.g., from agriculture)
- Water (surface, ground and deep ground water)
- Air (e.g., chemically changed particles)
- Soil movements in agriculture and silviculture

The resource categories can best be thought of as separate but equal measures for the impacts of resource extraction on the environment and are usually not added up [for reasons of comparison of different services it is possible though, to add up abiotic and biotic resources and soil movement or erosion in order to measure the “material footprint” of a service or product (see [9] for possible applications of this and other aggregations)] or weighted by their individual significance. Although a product may be very resource efficient in one category, it can be regarded not resource efficient if it shows comparable high material inputs in other categories. The resource categories are therefore looked at and compared separately. In this paper, only the categories abiotic resources, water and air are considered as the amount of resources calculated within the categories biotic resources and soil movements is not significant compared to that of the category abiotic resources (less than one percent).

The material input (MI in kg) refers to the service unit (S) generated electricity at grid connection point, measured in MWh:

$$\text{MIPS} = \frac{\text{MI}}{\text{S}} = \frac{\text{kg}}{\text{MWh}} \quad (1)$$

To consider all data life cycle wide, material intensity factors (MIT-factors) are being used. MIT-factors for different types of materials, modules and services are available online, published by the Wuppertal Institute [11].

3. Scope

3.1. System Boundaries

The system boundaries include the wind farm (wind turbines and internal cables) and grid connection [offshore platform(s), external cables]. System border is the particular point of connection to the inland high voltage power grid, including all net losses until this point. Regarding the WFBO1, parts of the onshore converter station “Diele” are also considered, as the construction of a second AC/DC converter is necessary to establish a HVDC transmission.

The life-time of turbines is assumed to be 20 years [4]. Within this period of time, maintenance and exchange of components with a shorter life-time like the rotor and gearbox are incorporated. Transports of components usually start at assembly point and are transports via sea vessels, train or lorry.

3.2. Assumptions and Limitations

Life-cycle oriented approaches to assess environmental parameters and impacts are in general subject to a broad difference in data quality, often use singular non-representative manufacturer data and rely on assumptions and appraisements for non-available information such as exact composition of components or energy demand for assembly. Thereby strict natural science procedures like verification or validation cannot be provided in most cases. In order to conclude if system A is nonetheless in advantage of system B in terms, e.g., of resource demand, this study employs a limit of significance of 10%. This means: As long as the difference in the results does not exceed 10% of the system with the highest resource demand, it is not possible to determine which system is better. When using the results of this study in another but comparable (MIPS analysis of energy production) context, it is to be advised to employ a higher limit of significance.

In cases where there was no primary data on the energy demand for the production and assembly of components available, the energy demand is estimated with the help of blanket addition factors [12]. These factors are based on data for the primary energy demand of processes in different industrial sectors. In doing so, this procedure is subject to the assumption, that all assembly and wrought material processes use 100% electrical energy from the national energy production mix. In this study, an overall majority of all assembly processes is assessed this way.

Production spill over incurring in the process of manufacturing wrought materials and components is evaluated using blanket material utilization grades of wrought material classes. A selection of these grades can be found in [13], which is based on supplier data. While assumed to be accurate enough for usage in a MIPS analysis, the data might be outdated (1998) in terms of today's material efficiency in the supply chain of wind turbine components and thus overrated.

The middle full load hours are a significant factor for the overall resource use of wind farms or any kind of energy production plants. As they are based on projections in this study, this can cause uncertainties in the results. In 2011, WFAV exceeded the prognosis achieving 4450 full load hours, which is about 15% more than projected [14]. Hence, the projected middle full load hours might be a conservative estimation.

It is common in life cycle assessments of wind turbines to assume a life time of 20 and sometimes even 25 or 30 years. This might be too optimistic as a recent study of wind turbines in the UK and Denmark showed [15]. A smaller life span of certain turbine parts such as the generator or rotor blades would highly influence the results of the study and should therefore be considered in future assessments.

The cut-off criteria for all assessments in this study accounts for 1% of the overall mass of the bill of materials as well as the material inventories of each single component.

4. Material Inventory

This chapter describes the main materials and necessary assumptions for each of the elements (turbine, connection and transformer) of the analyzed wind farms.

Data for the wind farms are mainly based on the studies [5,6]. However, in case of WFAV, the length of the external cables has been adjusted from 80 km, which was a conservative estimation, to 66 km [16]. For WFBO1, the basic assumptions on the exchange of spare parts have been aligned to WFAV's for reasons of comparison. Table 2 shows the wind farm's weight specifications. For the calculation, additional production spill over during assembly of components is included. Since WFAV and WFON turbines are of the same model, they show only marginal differences. The material inventory of the WFON is therefore described only briefly at the end of this chapter.

Table 2. Wind farm component weights (rounded).

Structure	WFAV	WFBO1	WFON
Wind turbine	1520 t/turbine	2590 t/turbine	4025 t/turbine
Internal cables	400 t (25 t/km)	3500 t (29 t/km)	53 t (9 t/km)
Transformer/converter platforms	1580 t	7410 t/4970 t	480 t
External cables (marine land)	5180 t (85 t/km 13 t/km)	9520 t (60 t/km 22 t/km)	542 t (- 12 t/km)
Mass per rated power	420 t/MW	580 t/MW	820 t/MW

4.1. Material Inventories of WFAV and WFBO1

In case of the turbine Repower 5M for WFAV, there was a high availability of primary data: Type and weight of components are based on data of the manufacturer Repower [17]. Since for the BARD 5.0 turbine only few primary data was available, it is assumed that—considering the similar technical data—main components like gearbox, generator and transformer are identical. Material compositions of components in general are derived either from declarations of the specific manufacturer, literature data or expert appraisements.

4.1.1. Rotor and Nacelle

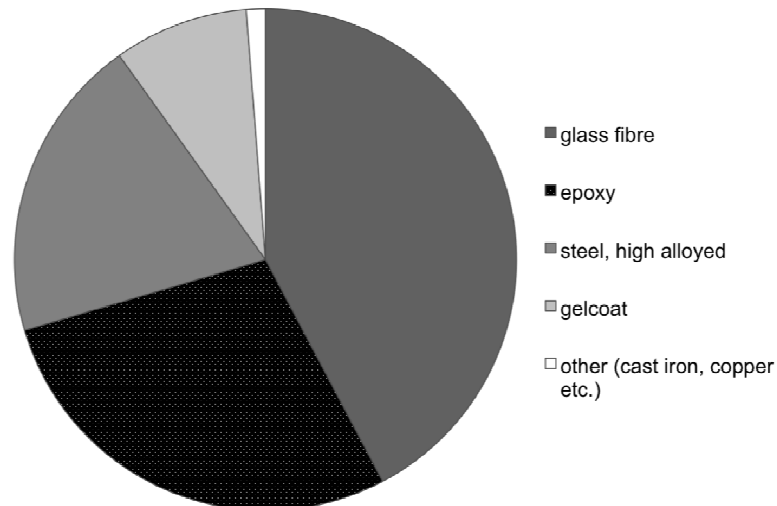
The Repower 5M rotor blade is a 19 t fiber reinforced epoxy construction of 61.5 m length. In contrast the BARD 5.0 blade is heavier (28.5 t on 60.0 m length) and its reinforced fiber design is furnished with a polyurethane (PUR) core, in which the bonding epoxy is injected by vacuum assisted resin transfer molding (VARTM). Thus, the amount of epoxy is reduced to a minimum and mainly replaced by PUR. Both blade types use gel coat for protective coating, steel for lightning protection and high alloyed steels for bearings. Data of the nacelle components of the Repower 5M are mainly based on manufacturer data (see [5] for reference). The BARD 5.0 Generator, its frame, the bearing as well as the azimuth-system are predominantly analogue to the 5M turbines of WFAV (see [6] for further reference). Figure 1 shows the composition of the Repower 5M rotor and its pitch equipment.

4.1.2. Tower and Foundation

WFAV's specific tower weight (4.7 t/m length) is distinctly higher than WFBO1's (4.1 t/m length). However, the weight of the Repower 5M tower is a conservative estimation based on the tower of a prototype [18], while specifications of WFBO1 were published in a press release [19]. The tower

material composition (more than 90% of it is low alloyed steel) is based on an assumption validated by the manufacturer.

Figure 1. Material composition of rotor and pitch-equipment of Repower 5M (WFAV).



The foundations in WFAV are conventional jacket foundations on four 33–44 m long foundation piles, weighting 766 t overall [20,21], while the WFBO1 uses newly constructed triple foundations. A triple foundation is built up of a massive (495 t) support cross standing on three 85–105 m long foundation piles (up to 450 t each). Both foundations consist mainly of low alloyed steel [22]. The coating is a mixture of epoxy and zinc.

4.1.3. Grid Connection

Wind turbines of WFAV are linked to a step-up transformer platform (30/110 kV, 75 MVA) connecting the wind farm to the 380 kV AC grid inland via 60 km of submarine cables and 6 km of land cables. WFBO1 is equipped with a similar transformer platform (33/154 kV, 2×208 MVA) and a converter platform, connected to the mainland via a 150 kV HVDC cable link, separated into 125 km submarine cables and 75 km land cables. On the mainland, a converter station converts HVDC back to HVAC. Weight specification and material composition of the transformer platform from WFAV is mainly taken from a component list of the manufacturer [23,24]. For WFBO1, masses of the platform substructure and topside are based on [25], while for the transformer equipment data from WFAV were scaled up. The weight specification of the HVDC platform derives from manufacturer data [26], whereas the composition of key components like the transformer was mainly assessed using genuine environmental product declarations of ABB AG (e.g., [27]). The jacket substructures of the platforms are assumed to be of the same kind as jacket foundations in WFAV. Weight and composition of submarine HVAC and HVDC cables is based on a cable manufacturer [28] and literature data [29]. While submarine cables have a copper core with a lead or plastic coat, land cables consist of an aluminum core with a plastic coat. The inventory of the land-based equipment for the DC/AC-switch (power conversion) is assumed to be idem to the switch in the offshore station.

4.2. Material Inventory of WFON

The WFON wind farm is assumed to be located in a flat area in central Germany with good wind speed conditions (7.3 m/s middle wind speed). The wind turbines are assumed to be the onshore version of the Repower 5M model placed in WFAV. Accordingly, the material inventory of the turbine equals WFAVs apart from minor changes in the nacelle. The towers height is 114 m, whereat the specific weight is much lower with 2 t/m length compared to that of WFAV (4.7 t/m length). The foundation is deep grounded and consists of reinforced concrete with a low alloyed steel amount of 4%. In general, the mass of onshore foundations are highly dependent on the place of location (earth structure). In case of WFON the mass is dimensioned in regard to a Repower 5M pilot plant [30]. The dimension of the transformer station is based on [31] and the transformer itself is assumed to be the same as in WFAV (75 MVA).

4.3. Recycling and End-of-Life

As defined in the convention of the MIPS concept [8], recycling of materials is not considered within the system but shifted into the system in which the recycled material is used as secondary raw material. Regarding the deconstruction phase of the wind farms, the same resource consumption (component transportation) as that of the construction phase is taken into account. It is assumed that the amount of components going to landfills is negligible.

5. Resource Use of the Analyzed Systems and Further Research

The results of this study document that WFAV has a significant higher resource use per MWh generated than WFBO1 in terms of abiotic resources, but not in water and air use (Figures 2 and 3). The higher abiotic resource use of WFAV is caused by the external submarine cables. Due to their high content of resource intensive copper in the core they alone account for 58% in the overall abiotic material input. In case of WFBO1, the resource use for the production of the wind turbines (head mass, tower and foundation) has a major share exceeding that of the grid connection in all three categories. However, the sum of BARD 5.0 foundations and towers outweighs the Repower 5M's by two times resulting in a 50% to 60% higher resource use depending on the resource category.

The comparison of resource use for the two grid connection options (platforms and external cable) indicates that the analyzed HVDC transmission is more resource efficient than the HVAC system in all categories, notwithstanding the considerable amount of copper and aluminum in the external cables over a distance of about 200 km and an additional 5000 t heavy HVDC platform applied with three 140 MVA transformers. This is mainly attributed to the higher specific copper demand of HVAC three-phase (In contrast HVDC transmissions are equipped with two-phase cables.) submarine cables in terms of length and transmissioned power. As wind farms in Germany are mostly planted large-scale in coast distances over 50 km [32], HVDC transmission allowing less power losses and smaller cable cross sections could be advisable economically and ecologically. Since the length of the grid connection is not the only adjustable parameter of wind farms, it cannot be concluded though, that HVDC connections are in general more resource efficient than HVAC connections. Additionally, the

HVAC cable connecting WFAV is presumably over dimensioned in relation to the transmitted power, since the cable seems not to be designed for the wind farm specifications.

Figure 2. Resource use of WFAV for the subsystems wind farm (turbines, internal cables), grid connection (transformer platform, external cables), use phase, construction and deconstruction.

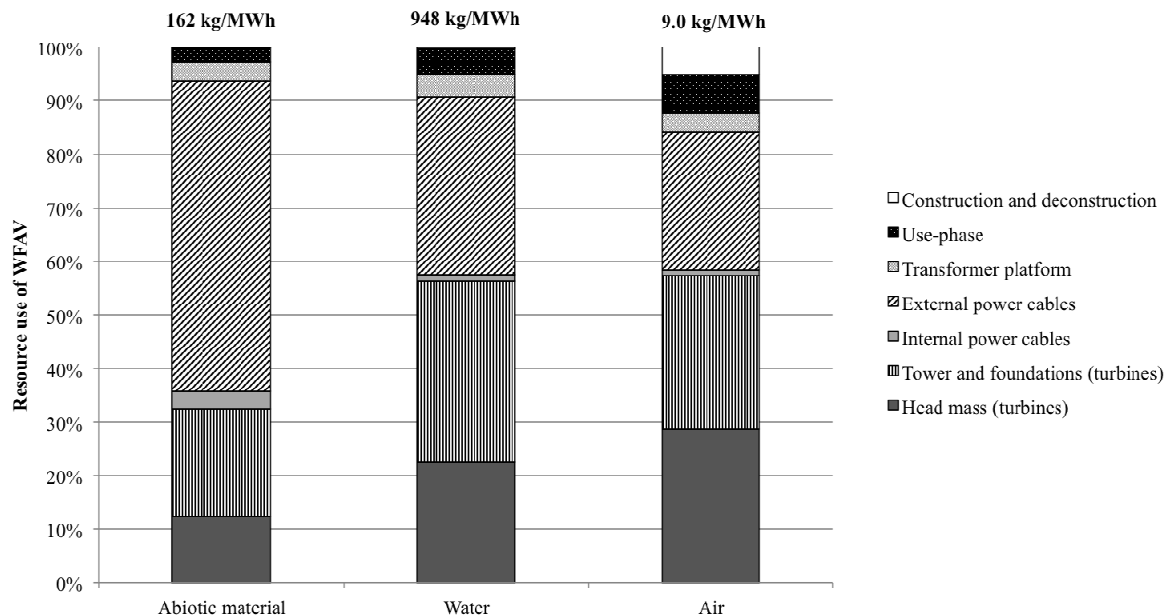
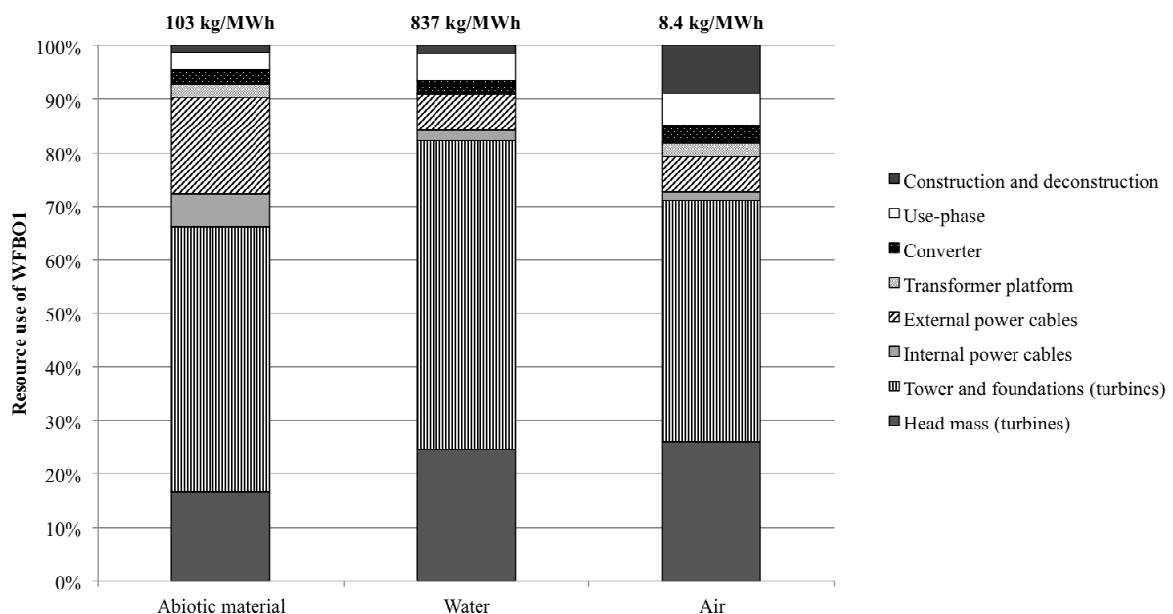


Figure 3. Resource use of WFBO1 for the subsystems wind farm (turbines, internal cables), grid connection (transformer and converter platform, external cables), use phase, construction and deconstruction.



By comparing WFON and the two offshore wind farms, both exceed WFON's abiotic resource demand, since its grid connection relies on a much shorter cable with aluminum core. However, there is reason to assume, that the deployment and interconnection of large offshore wind farms minimizes

this difference in resource demand, due to shared submarine cables, transformer stations and an overall higher energy yield [6].

Compared to the resource use of the German and European power mix as well as coal plants (see Table 3) it can be stated that all three wind farms are a resource efficient option to generate electricity. However, as electricity supply by wind energy is fluctuant, possible resource use for the power storage should be considered in future analysis. In addition it could become necessary at some point to enlarge the German power grid for wind energy transmissions to areas of high energy demand in the south of Germany, which would increase the overall resource demand of wind energy in general.

Even though direct comparisons to material intensity assessments of other renewable energy production systems such as solar energy are possible to some extent, they are not drawn in this paper due to either a lack of up to date data or test of accounting consistency. The data for coal plants on the other hand relate to the year 1997. Although efficiency of coal plants has increased since then, resource use will still be very high in consideration of the fact that there is a difference of some orders of magnitude between 1997 coal plants and modern wind turbines. They can therefore be safely used for a rough comparison.

For further information on the resource demand (and resource efficiency potentials) of other renewable energy systems the reader is referred to the studies [5,33,34], which among others analyzed biogas and concentrated solar power plants (see Table 3 for selected results).

Table 3. Material intensity of the assessed wind plants, the German and the European power mix.

Power plants	Abiotic Resources [kg/MWh]	Water [kg/MWh]	Air [kg/MWh]
WFBO1 (2012)	103	837	8
WFAV (2012)	162	948	9
WFON (2010)	90	843	8
German Power Mix [12]	3,150	57,640	510
European Power Mix [12]	1,580	63,830	420
Other energy systems (A direct comparison to the three wind farms was not conducted within this paper.)			
Coal plant, hard coal [8]	892	6,434	751
Coal plant, soft coal [8]	11,015	12,244	897
Biogas plant [5]	595	1,747	954
CSP, desertec scenario, central receiver [34]	120	4,928	9

On a strict micro-economic level without grid integration it would be advisable to include alternative wind turbine concepts, like middle-speed and direct-drive synchronous generators, in future assessments. These technologies, despite employing rare earth metals in their synchronous generators, could be more resource efficient because of their more compact and material efficient design. For onshore applications it would also be interesting to test weather two bladed wind turbines (less raw material per turbines) are more resource efficient than three bladed turbines. At present some of these issues are addressed in the “KRESSE” project [35] of the Wuppertal Institute regarding the material flows during the transformation of the German energy supply system.

6. Conclusions

This study shows that the analyzed wind farms are a very resource efficient alternative to generate electricity. The results are transferable to other offshore wind farms with similar coast distances and water depths, if the turbines are equipped with asynchronous double-fed induction generators. As such, the wind turbines are representative for the German offshore wind energy since 58% (Number based on constructed, under construction and approved offshore wind farms in the German North and East Sea until 2020 [36]) of the offshore energy output to be installed until 2020 will be produced by these generator types.

In terms of grid connection possibilities it can be concluded that HVDC connections are, despite requiring additional platforms, not necessarily less resource efficient than HVAC options. In fact, the HVDC connection assessed in the paper at hand showed a considerable smaller specific resource demand.

Although the analyzed fictitious (There are currently no onshore wind farms with such a number of 5 MW turbines.) onshore wind farm is more resource efficient than the offshore farms, there is reason to assume that higher energy yields in the offshore area could minimize this difference. It will not diminish completely though due to longer grid connections and steel foundations. In order to increase resource efficiency of offshore wind energy one might therefore aim to reduce weights of generator, gearbox and rotor so that towers and foundations can be designed lighter as well. This could be achieved by deploying alternative turbine concepts for large turbines, which are presumably more resource efficient (like middle speed synchronous generators).

In terms of possible further research on the resource efficiency of wind farms one could assess whether the cooperative operation of more than one wind farm is not only advisable in an economy of scale [26] but would also be more resource efficient. Under the circumstances that the massive offshore platforms for power transformation and conversion as well as grid connections are shared they are at least supposed to be more material efficient. According to the authors an enhanced use of offshore wind energy is absolutely necessary anyway in order to achieve wind energy targets assumed in most of the wind energy deployment scenarios such as the BMU Leitstudie 2012 [2].

Conflicts of Interest

The authors declare no conflict of interest.

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