



Method for holistic wind turbine drivetrain comparison exemplarily applied to geared and direct drive systems

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Abstract

The drivetrain as an important part of wind turbines needs to be improved in order to deal with today's high development and cost pressure. One important step towards enhanced drivetrains is to identify the most suitable concept for a targeted onshore application in an early design stage. With this purpose, a holistic lifecycle system evaluation approach relying on minimum input information is presented. In order to identify a dominant solution, an additive target system is defined taking cost, ecological sustainability, and supplied energy into account. This multi-criteria decision is aggregated by defining a macrosocial evaluation criterion: "drivetrain specific energy supply effort". A physics- and empirically-based model is developed to quantify the targets for different onshore drivetrain concepts. The validity of the model results is shown by a comparison to meta-analysis findings. Being utilized on a drivetrain concept comparison between geared and direct drive the approach's value is showcased. Both concepts score on a comparable level slightly differing in weak and strong wind regimes. An exemplary trade-off between investment- and operational effort shows, that for both concepts the investment effort is higher than the operational. The comparison furthermore shows how robust decision support can be provided by parameter variation and finally it stresses, that the decision maker's preferences need to be incorporated in the decision. Concluding, this analysis shows that physics- and empirically-based model approaches enable holistic wind turbine drivetrain concept comparisons in an early design stage.

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Methode zur ganzheitlichen Bewertung von Windenergieanlagen-Antriebssträngen exemplarische Anwendung auf den Vergleich von Konzepten mit und ohne Getriebe

Zusammenfassung

Um adäquat auf den heutigen Entwicklungs- und Kostendruck in der Windbranche zu reagieren, sollte eine Verbesserung des Windenergieanlagen-Antriebsstrangs im Fokus stehen. Wichtig ist es hierbei in einer frühen Produktentwicklungsphase ein optimal auf den Standort abgestimmtes Antriebsstrangkzept zu identifizieren. Ziel dieser Publikation ist die Vorstellung eines ganzheitlichen, den gesamten Produktlebenszyklus betrachtenden, Bewertungsansatz für Windenergieanlagen-Antriebsstränge, welcher ein Minimum an Eingangsdaten benötigt. Um das jeweils überlegene Konzept zu identifizieren, wird ein additives Zielsystem definiert welches Kosten, ökologische Nachhaltigkeit und die bereitgestellte Energiemenge berücksichtigt. Dieses multikriterielle Zielsystem wird zu dem makro-sozialen Bewertungskriterium „Antriebsstrangkzeptspezifische Energiebereitstellungskosten“ aggregiert. Zur Bewertung bzw. Quantifizierung der Zielerfüllung verschiedener Onshore Konzepte werden physikalische- und empirische Modelle entwickelt. Deren Validität wird durch den Vergleich zu Ergebnissen aus einer Metaanalyse nachgewiesen. Durch die Anwendung auf den Vergleich zwischen einem Antriebsstrangkzept mit und einem ohne Getriebe kann der Mehrwert dieses Ansatzes dargestellt werden. Beide Antriebsstrangkzepte schneiden im Vergleich ähnlich gut ab, unterscheiden sie sich jedoch in der Anwendung auf Starkwind- oder Schwachwindstandorte. Die Betrachtung eines exemplarischen Trade-offs zwischen Investitions- und Betriebskosten zeigt, dass für beide Konzepte die Investitionskosten schwerer ins Gewicht fallen. Durch den Vergleich kann zudem gezeigt werden, wie durch eine Parametervariation die Robustheit der Ergebnisse analysiert werden kann. Zudem zeigt die Anwendung, dass die entscheidungspersonenspezifischen Präferenzen in der Entscheidung berücksichtigt werden müssen. Zusammenfassend ermöglicht der vorgestellte Bewertungsansatz, basierend auf physikalischen und empirischen Modellen, die Durchführung von robusten und ganzheitlichen Windenergieanlagen Antriebsstrangkzept-Vergleichen in einer frühen Produktentwicklungsphase.

1 Introduction

Wind and solar power play an important role in realizing the German energy transition [1]. Facing the decarbonization of the mobility, industry, heat and electricity sector the needed renewable electricity amount will more than double between today and 2050 in Germany [2]. If Power-to-X and other storage technologies are included to strengthen the energy system, there is an even higher demand for cheaper renewable electricity, due to the losses in conversion processes [3]. Therefore, high investment in wind and solar capacity is definitely required. Nevertheless, reduced or foreseeable expiring feed-in remuneration schemes diminish the attractiveness of investments into wind power projects. This puts the whole wind industry under cost and development pressure. The average bid awarded in the German onshore tendering in December 2020 was 5.91 Ct/kWh [4]. This can be used as an indicator for the levelized cost of energy (LCOE) for electricity provided by onshore wind power. The average revenue source on the electricity market, the day-ahead price, was on average at 2.9 Ct/kWh in the respective year [5]. In order to overcome this huge discrepancy, between future revenue potential and energy supply expenses, technological development is needed.

The wind turbine drivetrain, as the sum of the energy converting components between hub and transformer, has a significant influence on the turbine's properties and costs. 34% of the turbine's investment cost can be accounted for

the nacelle and its components [6]. In this consideration nacelle includes the housing and auxiliary equipment on top of the tower in addition to the drivetrain. Over 80% of the unplanned failures of a turbine can be traced back to nacelle components [7]. In the partially rated range over 15% of losses can have their origin in the energy conversion within the drivetrain [8]. 10–20% of the overall turbine CO_2 -emission can be traced back to the drivetrain [9]. Concluding a holistic evaluation of wind turbine drivetrain concepts over their entire lifecycle should be the logical response to the prevalent development and cost pressure.

Innovation in general and in the wind turbine's drivetrain is mainly motivated by the goal to have a better product. In this context better product is defined as a product that is improved in any reasonable regards(s). Decisions made in the early design stage have the highest influence on the final product [10]. However, the early design stage, when concept and design decisions are made, is characterized by a high degree of complexity, uncertainty, and information deficits. Decisions have to be made about products which will be introduced into the market in two to five years under changed market conditions. Moreover, cost due to changes in the product design disproportionately increase with the maturity level of a product [10]. In order to avoid cost drivers in the later stages of the product lifecycle, the drivetrain should be analyzed holistically over its entire lifetime in an early design stage.

In today's market, mainly three different conventional drivetrain concepts can be distinguished: geared also known as high-speed, direct drive also known as low speed and finally mid speed concepts. Underlying are different technical ideas about the best way to carry and convert mechanical into electrical energy leading to distinct characteristics in the different life cycle stages. High-speed concepts are based on the idea, that a transformation of the rotational speed and torque with the help of a gearbox makes it possible to use smaller generators for the mechanical-electrical transformation. It moreover enables to make use of an asynchronous generator concept (doubly fed induction generator (DFIG)), which just needs a partially rated converter. Due to the less complex and lighter generator and converter the drivetrain mass is comparably low. Nevertheless, using the component gearbox adds more energy losses to the system and a source of failure due to high rotating parts. Whereas the direct drive concept waives of the component gearbox and instead needs enlarged synchronous generators, which are either permanent magnet or electrically excited. They rely on a fully rated converter. Getting rid of the component gearbox can increase the system's energy conversion efficiency and might increase its reliability. Nevertheless, lower input speed and higher input torque will lead to more pole pairs and a stiffer generator structure needed. This often results in a heavier drivetrain system, which needs more material and therefore more CO_2 -emissions are emitted in this lifecycle stage. Depending on the generator concept a dependency of the availability and price for rare earth is possible. In the following, high-speed concepts are referred to as geared and low speed concepts are referred to as direct drive. Mid speed concepts available in the market adopt aspects of both aforementioned concepts. They use a gearbox to increase the rotational speed but have a lower ratio than the high-speed concepts. Therefore, they mainly use a permanent magnet synchronous generator (PMSG) and need a fully rated converter. Reducing the generator weight

and complexity by increasing the rotational generator input speed while having a small gearbox might have the potential to result in a lighter system compared to geared and direct drive concepts. Still efficiency losses due to the gearbox and the possible dependency on rare earth material exists. Concluding all concepts have specific advantages and disadvantages in different lifecycle stages, by looking at them individually it is not possible to identify the best system.

Casting a glance into currently available literature shows, that some wind turbine drivetrain concept comparisons have already been conducted. Fig 1 illustrates the used evaluation criteria as well as the best performing concept in the respective comparison. It is visible that a multitude of different criteria is used. Nevertheless, there is no approach yet available including a holistic set of criteria. This means considering the entire lifecycle as well as influences of and interdependencies between different drivetrain components. Some authors already marked this critically [11, 12]. Moreover, the comparisons are highly dependent from underlying assumptions the authors make. In some publications these assumptions are not transparent, not understandable or not generalizable. Furthermore, underlying uncertainties vary with the evaluated drivetrain concept [13]. These can be reasons for diverging comparison results while comparing with regards to the same evaluation criteria. This becomes extremely visible when analyzing the operational phase. Some sources recommend geared drivetrains [14–16] while others suggest using direct drive concepts [13, 17] for the same application. Concluding literature approaches are not yet able to sufficiently support the early stage drivetrain concept decision.

To fill this gap the present study aims to consider the effects the drivetrain decision can have on the entire turbine's lifecycle in one holistic approach with minimal input information. It targets the quantification of trade-offs of different drivetrain concepts in different lifecycle phases. In order to evaluate and compare presently available drivetrain

Fig. 1 State of the art in literature. *DFIG* doubly fed induction generator, three stage gearbox and partially rated converter, *PMSG* permanent magnet synchronous generator as a direct drive with a fully rated converter, *Mid speed PMSG* permanent magnet synchronous generator, two stage gearbox and fully rated converter, *3-pt. susp.* three-point suspension system, *Susp.* suspension system

Source	Evaluation criteria						
	Investment cost	Operational cost	Availability	Reliability	Efficiency	Drivetrain mass	Sustainability
[11]	DFIG				PMSG		
[14]		DFIG					
[21]			PMSG				
[15]				DFIG			
[22]	PMSG (offshore)						
[22]			PMSG				
[13]	3-pt. susp.						
[12]	Mid speed PMSG						
[23]			DFIG				
[24]						Susp.	
[25]							DFIG
[26]	Low/mid speed PMSG						

configurations, a physics- and empirically-based model is presented which can be applied in an early drivetrain concept decision [18–20]. A great emphasis has been put on the wide parameterization of the model in order to allow a broad application in an early design stage despite of the lack of data. The default model parameterization is based on literature data. But it can be easily customized with industrial data from an wind turbine original equipment manufacturer (OEM), which will improve the result's accuracy. The model is built up on three pillars:

- A physics-based lifecycle costing approach
- An ecological sustainability approach
- An annual energy production approach

The publication is structured as follows. The overall model approach and the used sub-models are presented in Chap. 2. In a case study, the developed approach is applied on the comparison between geared and direct drive concepts. The results are presented in Chap. 3. Finally, Chap. 4 concludes and gives an outlook.

2 Model

The overall goal in the design stage of a drivetrain is to find the most suitable solution. Rephrased, the design engineers are looking for a system solution which is dominant against the alternatives when taking the entire lifecycle of the system and possible changes in external influencing factors into account. In order to be able to quantify this dominance, an additive target system is defined using a bottom-up approach. The target system is compiled by the following three targets in order to make it fundamental, complete, redundancy-free and unbiased:

- Minimal lifecycle cost,
- Maximal sustainability over the lifecycle and
- Maximal energy supply over the lifecycle.

For solving this multi-criteria weighting problem, the authors recommend using the trade-off approach for identifying the decision-makers' specific weighting between the three targets. Practical advice is presented in von Nitzsch et al. 2014 [27]. This additive target system has the advantage, that customized preferences for individual OEM application are easily implemented.

Within this paper the solution mostly complying with a macrosocial perspective is of interest as it is generalizable and this way of interest for most readers. From a macrosocial perspective, a system solution complying with the German energy policy target triangle (reliable, cost effective and environmentally friendly electricity supply) is in favor [28]. Therefore, a comparative figure, "drivetrain specific

energy supply effort" (DSE), is defined in analogy to the LCOE metric for the drivetrain, please compare Eq. 1 [29]:

$$LCOE = \frac{I_0 + \sum_{t=1}^{20} \frac{O_t}{(1+i)^t} + \frac{I_{21}}{(1+i)^{21}}}{\sum_{t=1}^{20} \frac{E_t}{(1+i)^t}} \quad (1)$$

I_0 accounts for the initial investment, which means cost for material, manufacturing, transport and installation of the drivetrain. O_t includes cost arising during the operational phase. They are taken into account in the time of origin t . End of life cost are considered by I_{21} , as it is assumed that the drivetrain is deconstructed after 20 years of operation. The discount rate is depicted by i . E_t accounts for the electricity supply in the respective year t of the entire turbine. The lower LCOE the less expensive a drivetrain can supply electricity.

In contrast to LCOE, the metric DSE internalizes external cost due to CO_2 -emissions emitted during the product's lifecycle. Emissions are monetarily taken into account by using the price of CO_2 -certificates (25.15 €/t in May 2020 [30]). Furthermore, only the lifecycle of the drivetrain is considered with cost and emission in the metric DSE. The amount of electricity provided is, however, related to the entire turbine. Similar to the LCOE, the time of cost-, emission- or electricity-emergence defines when these quantities are taken into account, please compare Eq. 2:

$$DSE = \frac{I_{0(e+c)} + \sum_{t=1}^{20} \frac{O_{t(e+c)}}{(1+i)^t} + \frac{I_{21(e+c)}}{(1+i)^{21}}}{\sum_{t=1}^{20} \frac{E_t}{(1+i)^t}} \quad (2)$$

$I_{0(e+c)}$ accounts for the initial investment, which means cost and emission for material, manufacturing, transport and installation of the drivetrain components. $O_{t(e+c)}$ includes cost arising and emission emitted during the operational phase. They are taken into account in the time of origin t . End of life efforts (cost and emission) are considered by $I_{21(e+c)}$, as it is assumed that the drivetrain is deconstructed after 20 years of operation. The discount rate is depicted by i . E_t accounts for the electricity supply in the respective year t . The lower DSE is the better a concept fulfills the set requirements.

In order to quantify the different concepts' target manifestation physics and empirically-based models are developed. The model's goal is to quantify the influence the technical drivetrain concept choice has on the different lifecycle stages in terms of cost, supplied energy and CO_2 -emissions. Fig. 2 gives an overview about the model structure. The entire lifecycle of an onshore wind turbine drivetrain is evaluated by the model. For every life stage, a sub-model has been developed. Different drivetrain components are differentiated based on their functionality. A modular approach is used. The sub-models are implemented in a way that concept (un)specific parameters (like material prices, failure

rates, specific emissions e.g.) can be easily adjusted if updated information or knowledge is available. Model input are general requirements for the application of the drivetrain which are usually available in an early design stage, e.g. rated power and rotor diameter. Model output is a quantification of the target system. It is implemented in Matlab. In the following, the manifestation of the used sub-models and the main underlying ideas and assumptions are briefly described.

2.1 Rough designing of components

The rough designing of the mechanical drivetrain components (suspension system, gearbox and mainframe) is mainly based on approaches developed by the National Renewable Energy Laboratory (NREL) based in the United States of America [31, 32]. Considering the main loadings of the component, its geometry and mass are estimated based on physical and empirical relationships. This way the approach is scalable, and the impact the design choice for one component has on the rest of the drivetrain system can be captured. Generator and converter mass are estimated based on regression functions from [32].

2.2 Material effort estimation

Based on the estimated component mass, the material effort, defined as the semi-finished product, is estimated in this sub-model. Average component specific material distributions are derived from available literature sources [33–42]. A two-step approach is then used to estimate the semi-finished product effort. First, literature sources about raw material prices are compiled. With the help of the GENESIS database of the German federal statistical office, the processing effort from raw material to semi-finished product in terms of cost is estimated [43]. For emissions, literature provides material specific emissions which are used [44–49].

2.3 Manufacturing effort estimation

The manufacturing cost estimation is based on a generative, bottom-up approach. As a first step, the components manufacturing is split up into its most important process steps. The machine-hour-rate calculation then allows to estimate the manufacturing effort for these defined process steps [50]. For estimating the needed machine runtime, components geometry and average process parameters, derived from literature, best practices and expert interviews, are used. A more detailed presentation is available in [36]. For the emission estimation in this lifecycle phase, literature provides a manufacturing surcharge for process energy which is used in this approach [51].

2.4 Transportation effort estimation

The transportation effort estimation approach is based on interviews with practitioners [52, 53]. Component mass and geometry are modelled as factors influencing rent of transport vehicles, needed equipment, and wages. Incidental transportation cost cannot be quantified in an early design stage; therefore, a risk classification is used in this approach. This way it is possible to indicate if a certain drivetrain design might lead to high incidental transportation effort in an early design stage. Emissions due to the use of fuel for the transport vehicle are considered for the transportation phase.

2.5 Installation effort estimation

In this approach installation effort is modelled as effort for the needed equipment for lifting the drivetrain on the turbine tower (crane). Based on hook height and lifting load an industrially available crane is chosen from a database [54]. The equipment cost is composed by a fixed and a variable part. Fixed are the expenses for journey, installation, disassembly and departure of the crane. Variable is the duration of the installation, which influences the renting fee as well as wages. Emissions due to fuel used for the identified crane are considered for the entire installation phase.

2.6 Operational effort estimation

Planned maintenance is considered by semi-annual inspections whose durations are influenced by the constituting components of the drivetrain concept. For example, for concepts relying on a complex lubrication system, additional treatment is considered. From a sustainability point of view emissions due to using a vehicle for planned maintenance are considered.

For modelling the unplanned operational drivetrain behavior, a statistical approach based on Monte Carlo simulation is developed. The most relevant influencing factors are considered by modelling failure rate, downtime, failure severity and duration of repair and replacement as uncertain factors. Their manifestation is based on literature sources. This way it is possible to estimate the labor, material, and equipment expenses which are caused by unplanned failures during the operational phase. A more detailed presentation and application of this sub-model is available in [20]. Reason for emissions, arising from unplanned operational measures, are owing to fuel for vehicles, material and manufacturing of spare parts and crane fuel consumption if needed.

Table 1 Literature sources for comparative figures in the meta-analysis

	Drivetrain investment cost	Drivetrain operational cost	CO ₂ -lifecycle-emission	Levelized cost of energy
Sources	[56–61]	[62–69]	[9, 70–73]	[62–67, 74–90]

Table 2 Drivetrain concept characteristics

Concept	Suspension system	Gearbox type	Generator type	Converter	Market share [%] [94]
3P-3G-DFIG-PC	4-point	3-stage	DFIG	Partially rated	40
MB-PMSG-FC	Moment	–	PMSG	Fully rated	10

2.7 End of life effort estimation

For disassembly, the described installation sub-model is used as it is assumed that the same crane will be utilized. Transportation effort is estimated by the presented transportation effort estimation. Based on literature recycling of the component's material is considered. Emissions during disassembly and transportation are considered similar to the way described in the transportation and installation effort estimation. Emissions saved due to recycling of metal, rare earth and lubricant emissions are credited in the overall balance.

2.8 Efficiency estimation

For estimating the concept's efficiency, component design specific power curves from literature are used [8, 55]. They are normalized to the rated power and therefore scalable in the model's approach.

3 Model validation

In order to validate sub-model results with this current literature based parameterization, the method of meta-analysis

is utilized. With the help of this secondary analysis technique, empirical study results are aggregated to intervals of comparative figures manifestation. By comparing the model results to the comparative figures from literature, an indication about the model's validity becomes possible. Due to the poor availability of data in literature, all obtainable sources are used which are listed in Table 1. The validation is conducted for two prominent drivetrain concept. Table 2 gives an overview about the chosen concepts' characteristics.

The validation results are presented in a boxplot with four comparative figures (c.f. Fig. 3). The category literature I indicates the extreme values (min and max) from literature whereas literature II represents the mean and standard deviation. The results for the concepts introduced in Table 2 are based on a parameter study with a rotor diameter varying between 80 to 160 m combined with a rated power varying between 2 to 4 MW, respectively. This represents a historic turbine configuration. The reference site from German renewable energy act is used [91]. Implemented with an average wind speed of 6.45 m/s at 100 meter and a Weibull form factor of 2.1396.

For calculating the drivetrain's share on turbine investment cost, the model results are related to a literature average value for turbine investment of 1,010 €/kW [92]. Turbines sold for 2020/2021 aim at prices around 736 €/kW,

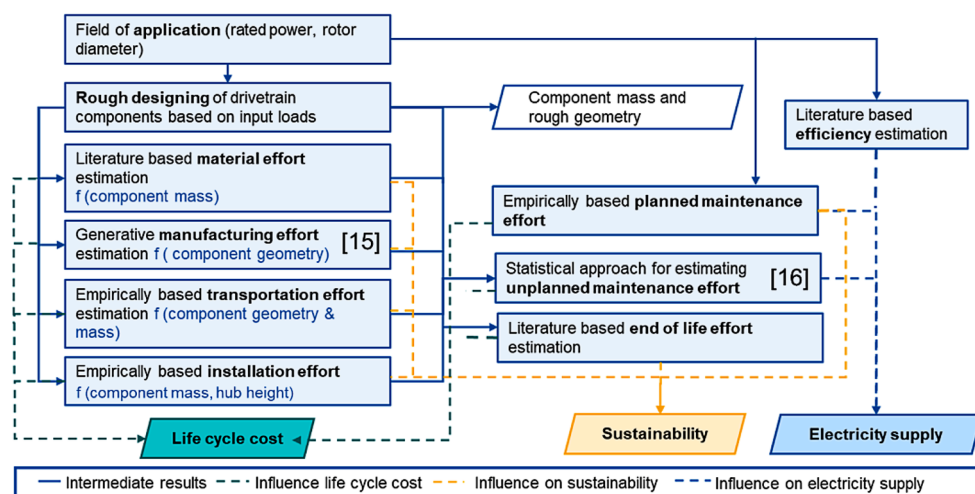
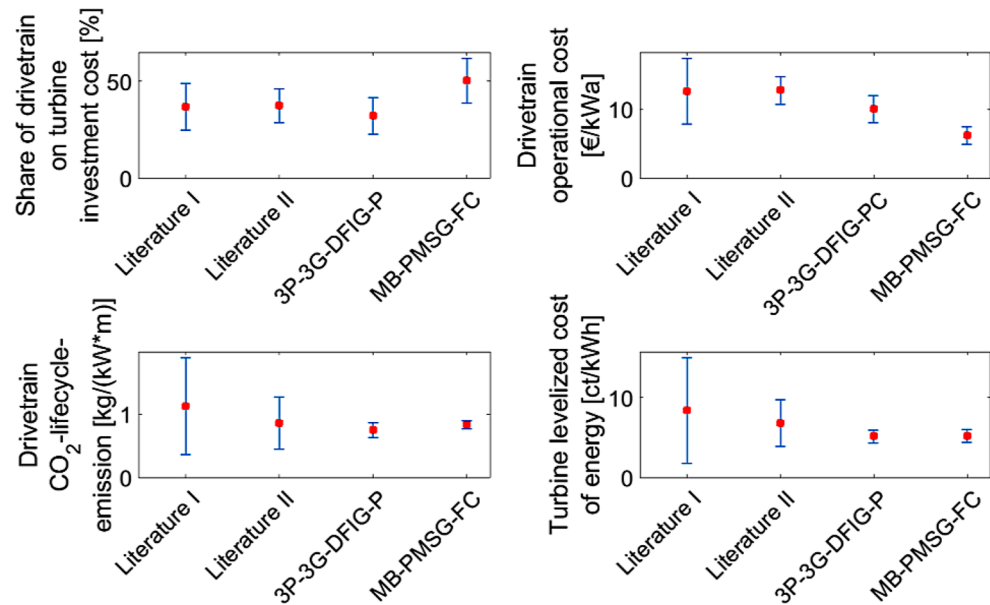
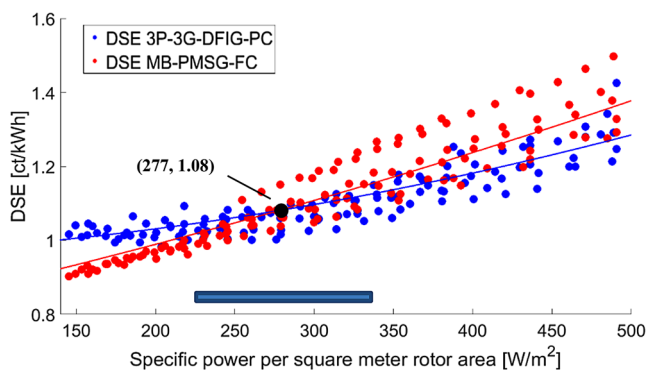
Fig. 2 Overview of the model structure

Fig. 3 Model results compared to meta-analysis findings

reasons for this decrease are lower margins in the entire supply chain and improved design [93]. Nevertheless, the historic value is chosen here in order to align with the other meta study sources. Looking at Fig. 3 the mean values of the considered concepts are within the literature bandwidth for the investment cost share. As the sources used in the meta-analysis are all of age, the authors assume that mainly geared concepts are considered here. Nevertheless, the model reflects the fact that the direct drive concept MB-PMSG-FC leads to a higher share of the drivetrain on the overall turbine investment cost, which is known in literature [11, 22]. Drivetrain operational cost is slightly underestimated for both concepts. Though, the mean result of both concepts is within the “literature I” boundaries. The qualitative comparison between the two concepts in terms of operational cost reflects common knowledge in literature e.g. [13]. Drivetrain related CO_2 -emissions over the lifecycle are calculated based on sources estimating the en-

tire turbines lifetime emissions. It is assumed, that 10–20% of these emissions can be traced back to the drivetrain [9, 72]. Model results for both concepts are within the broad literature boundaries. Furthermore, literature confirms the differences in CO_2 -lifecycle-emissions between the concepts visible in Fig. 3 [25]. The leveled cost of energy for the two concepts are both within the meta-analysis boundaries. In general all model results are above 5 ct/kWh, which vaguely corresponds to the auction results in Germany [4].

This way the model results of this literature based parameterization in general seem plausible as the orders of magnitude for the comparative figures are met and advantages and disadvantages of the different concepts are represented in the model results. Concluding, this analysis shows that with the help of physics- and empirically-based model approaches, viable wind turbine drivetrain concept comparisons are possible from a holistic point of view in an early design stage.

**Fig. 4** Concept comparison with regards to DSE

4 Case study: Comparison of geared and direct drive wind turbine drivetrain concepts

Within the following chapter the presented approaches applicability for supporting drivetrain design decisions is showcased. Therefore, a parameter study for today’s and near future’s turbine configuration is conducted for the two drivetrain concepts 3P-3G-DFIG-PC and MB-PMSG-FC (c.f. Table 2). The rotor diameter is varied between 80 to 200m in 10m steps. The turbines hub height is varied in accordance with changes in the rotor diameter (hub height = 40 m + $\frac{1}{2}$ rotor diameter). Whereas the rated power

Fig. 5 Concept comparison with regards to DSE while varying rotor diameter and rated power

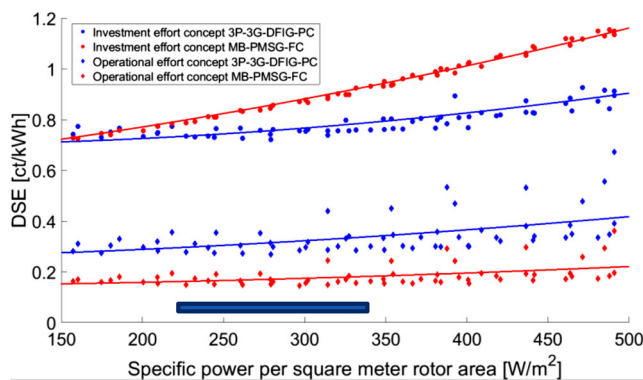
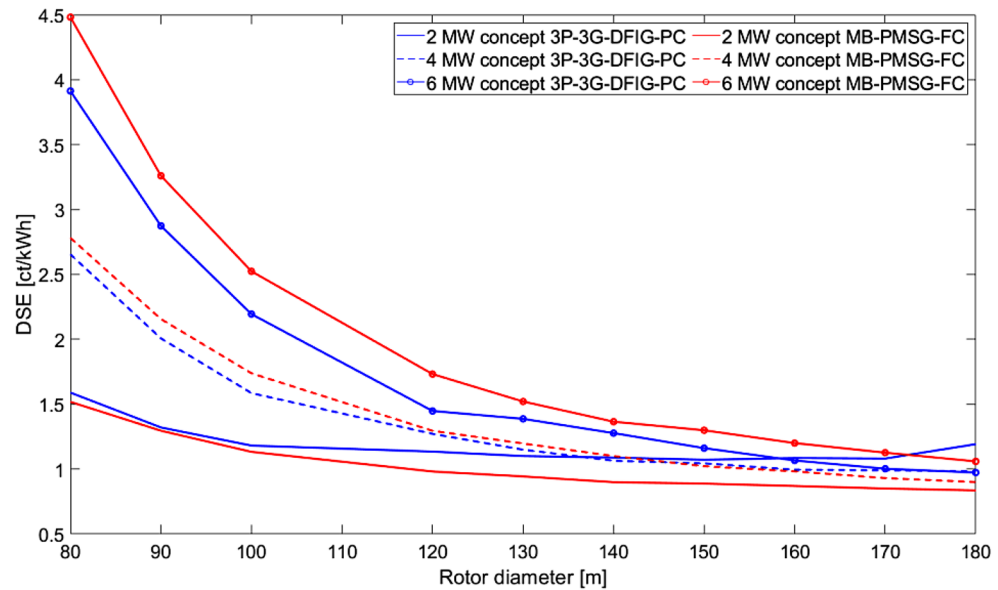


Fig. 6 Concept comparison with regards to the investment and operational phase

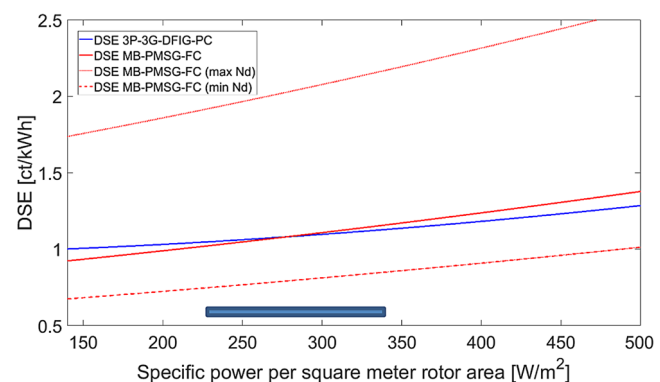


Fig. 7 Concept comparison with historic extreme neodymium material prices

is modified in the interval of 2 to 7 MW in 250 kW steps. The same site characteristics as for the meta study are assumed.

In Fig. 4 the conducted comparison is depicted. The x-axis represents a comparative value describing the requirements with respect to rated power and rotor diameter. The blue bar just above the x-axis indicates the characteristics of currently available turbines on the market varying between 229 and 340 $\frac{W}{m^2}$ [95–98]. These turbines are going to be installed in the coming years. On the y-axis, the derived comparative value DSE (c.f. Equation 2) for identifying the favorable system solution from a macrosocial perspective in the model framework is plotted.

Focusing on the near future turbines field of application both concepts scatter on a comparable level. Therefore, no concept seems clearly dominant about the other. Several rotor diameter and rated power combinations can result in the same specific power per square meter rotor area. It is site

dependent if a bigger rotor combined with a higher rated power is superior over a shorter rotor combined with less rated power and the same specific power per square meter rotor area. Using a regression function for both concepts, an intersection at 277 $\frac{W}{m^2}$ is apparent. Though it needs to be taken into account, that individual dots have to be compared for a design decision. This way 277 $\frac{W}{m^2}$ is not a strict line but can be interpreted as an indicator for a change in the concepts favorability. Based on the analysis a slight trend can be derived that drivetrain concept 3P-3G-DFIG-PC might be more suitable for stronger wind applications whereas concept MB-PMSG-FC seems better qualified to be applied in the weak wind regimes for the analyzed site and the underlying assumptions. As indicated in Table 2 both concepts are widely deployed in the market. The above presented result gives an answer to why we nowadays see both concepts in the market from a technological point of view.

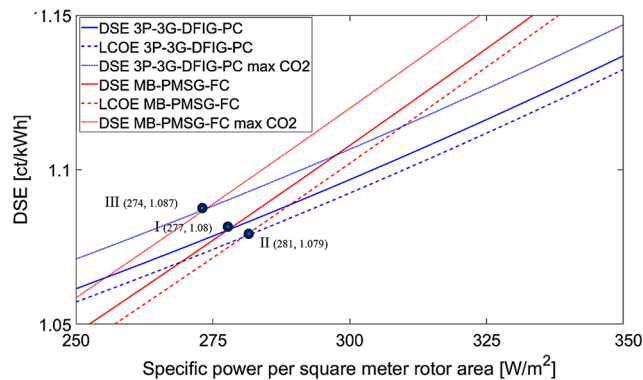


Fig. 8 Concept comparison with regards to DSE, LCOE and changed CO_2 -certificate price

Fig. 4 allows a concept comparison for different areas of application indicated by the specific power per rotor square meter. Fig. 5 now enables DSE statements about specific rotor diameter and rated power combinations. For the assumed site conditions (rather weak wind regime) it becomes visible, that a rotor diameter above 120 m is more advantageous for most applications. Thus a larger rotor diameter leads to disproportionate growth in energy supply compared to growth in cost and CO_2 -emission. Moreover it shows that for lower rated power applications (2 MW) the direct drive concept has advantages over the entire range of rotor diameters in terms of DSE. Whereas for medium and high rated power (4 & 6 MW) the geared concept results in the lowest DSW per rotor diameter.

In order to understand what causes this behavior, it is of interest to explore the influence of the different drivetrain lifecycle phases on this score. Fig. 6 therefore allows to analyze the trade-off between investment and operational phase on the overall DSE. End of life is integrated into the operational phase in this figure. For both concepts under investigation the investment phase has a higher impact on the lifecycle DSE than the operational phase. It increases with the specific power per square meter rotor area for both. Nevertheless, the slope for concept MB-PMSG-FC is much steeper, the higher the specific power per square meter rotor area becomes. So, the direct drive concepts result is more sensitive to increased rated power application compared to rotor diameter. For low specific power per square meter, deciding for a direct drive concept can even lead to the lowest impact in the investment phase. The changes in the operational phase due to changed drivetrain application area are relatively comparable. Hence the geared concept 3P-3G-DFIG-PC starts at a higher initial point and has a slightly steeper slope. Knowing these relationships, concept specific areas for improvement can be identified.

As stated in the model description, an advantage of this approach is the possibility to incorporate external developments which impact the concepts performance e.g. volatil-

ity in raw material prices and this way shortages in their availability. In the following it is shown, how the developed approach can support in this way. Figs. 4, 5 and 6 depict results valid for a specific set of external influencing factors. In order to assess the robustness of a concepts favorability against changes in these external influencing factors, they can be varied and the influence on the results be analyzed. In Fig. 7 this is exemplarily depicted for the historical extreme values of the material price for neodymium, the material used in PMSG because of its permanent magnetic characteristics. The starting price is the neodymium price of today (calendar week 6 in 2021) 116.81 €/kg [99]. It is compared to the ten years minimal material price 25.75 €/kg in January 2010 [100] and the ten years maximal price of 415.11 €/kg in June 2011 [101]. A huge impact on the concepts favorability is visible for the regression functions for each scenario. For an application in a design decision, design engineers need to assess which factor variability they expect for the future and conduct several analysis with changed external influencing factors. This way a more robust decision support can be provided.

Finally, the introduced macrosocial evaluation criteria DSE as a first step to include cost-to-society (including external CO_2 -cost) is contrasted to the popular metric LCOE in Fig. 8. As DSE incorporates cost for CO_2 -certificates it is in general higher than LCOE, visible in the plotted regression function in Fig. 8. As distinct drivetrain concepts perform differently in terms of sustainability, the metric choice for conducting the comparison can have an influence on the advice derived from the model results. This in particular becomes apparent when the CO_2 -certificate price is increased. The lighter colored regression functions in Fig. 8 depicts the model results for an estimation about CO_2 -certificate price in 2030. This is based on a white paper's assessment of the needed CO_2 -certificate price in 2030 in order to achieve the German climate goals (75 €/kg) [96]. Applied to the formerly used example it becomes visible, that including the ecological part of sustainability by internalizing external CO_2 -emission costs (in DSE), leads to a better performance of the geared concept 3P-3G-DFIG-PC in the used parameterization. Therefore, the authors stress to invest some time to identify the metric which represents the decision-makers' specific preferences in order to reasonably support the design decision.

All previously shown figures depict characteristics derived from historic relationships and correlations. This way the past can help predict how the future might look like. Furthermore, it offers the opportunity to foresee the impact technical changes can have on the overall systems solution favorability. Nevertheless, the authors stress to update all input data before applying this model. Especially for an OEM the ecosystem it operates in needs to be (indirectly)

addressed in the input data or at least kept in mind when using the model results for decision support.

5 Conclusions and outlook

To support the decision making of engineers in the design stage of wind turbine drivetrains an evaluation approach is developed. By using a holistic set of criteria this approach makes it possible to include the entire drivetrain's lifecycle as well as influences of and interdependencies between different components and the underlying trade-offs into the decision. The authors showed that with the help of physics- and empirically-based models a sufficient quantification of the systems characteristics over the lifecycle is possible. A great emphasis has been put on the wide parameterization of the model in order to allow a broad application in an early design stage despite of the lack of data. The default model parameterization is based on literature data. But it can be easily customized with industrial data which will improve the results accuracy.

By utilizing the approach for a drivetrain concept comparison for today's and near future's turbines application it becomes visible how this approach can be used and how valuable its application is. The comparison of a geared and a direct drive concept shows that both concepts score on a comparable level slightly differing in weak and strong wind regimes. Using this approach to examine the design trade-off between investment and operational effort, both concepts under investigation were shown to be more influenced by the investment phase than by the operational, though they differ in their sensitivity. A further analysis varying raw material prices stressed, that parameter variation analysis is needed in order to provide robust decision support. Comparing a macrosocial decision metric to the popular LCOE metric emphasizes, that decision-makers' specific preferences need to be incorporated in order to supply valuable decision support. Finally, the authors stress to update all input data before applying this model.

Future work should increase the sustainability perspective in this approach. It can be broadened with more ecological indicators as well as social aspects. A challenge is to implement it on a high aggregation level, as a lot is unknown in an early design stage. However, currently available Life Cycle Assessment and Social Life Cycle Assessment approaches need detailed information about the products lifecycle. Therefore, some research needs to be done in order to establish a joint interface between these two approaches. In addition, the developed approach should be integrated into virtual product development in order to increase and improve the data basis for the analysis. This way cost drivers in the later stages of the product lifecycle can be avoided. Furthermore, a final product becomes

more sustainable in terms of cost and ecology, the earlier a holistic perspective is taken in the development process. The entire framework is furthermore suited for offshore application. To deploy it offshore, transportation needs to be modelled in a different way and a sub-model including the weather conditions has to be incorporated.

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