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INFLUENCE OF THE STRUCTURAL INTEGRITY MANAGEMENT ON THE LEVELIZED COST OF ENERGY OF OFFSHORE WIND: A PARAMETRIC SENSITIVITY ANALYSIS

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Abstract.

The levelized cost of energy (LCoE) is an important measure to quantify the macro-economic efficiency of an offshore wind farm and to enable a quantitative comparison with other types of energy production. The costs of the structural integrity management - which is required to ensure an adequate lifetime reliability of the turbine support structures - are part of the operational expenditures of an offshore wind farm. An optimization of the structural integrity management may reduce the operational expenditures and consequently the LCoE. However, the effect of the structural integrity management on the LCoE is hardly known. To investigate this effect, this paper presents a sensitivity analysis of the LCoE of a generic offshore wind farm. The probabilistic models of the parameters influencing the LCoE are based on a literature study including an explicit model for the structural integrity management. The analysis reveals that LCoE may potentially be reduced if an optimization of the structural integrity management enables a service life extension.

Keywords: Levelized cost of energy, sensitivity analysis, structural integrity management.

1. Introduction

In the context of the energy transition in Germany and the European Union, the relevance of renewable energy is steadily increasing in contrast to conventional energy sources such as coal-fired power plants. Besides hydropower and solar energy, offshore and onshore wind energy is becoming a major part of renewables energies and is likely to be expanded in the future.

Over the past 20 years, the total number of wind turbines increases from 9400 to 29600 in Germany, whereof 1500 wind turbines with a total capacity of 7.7 GW are currently installed offshore [1, 2]. According to the EU strategy presented by the EU Commission in 2020, €800 billion will be invested in offshore renewable energy over the next 30 years to increase the capacity of offshore wind energy from 12 GW to 60 GW by 2030 with an aim to reach a total capacity of 300 GW by 2050 [3].

In addition to the investments in the expansion of renewable energy, however, the efficiency of renewable energy sources measured in terms of the levelized cost of energy (LCoE) must also be considered to ensure that these energy sources are competitive. As an example, in 2018 the LCoE of offshore wind energy in Germany was still higher than the LCoE of other main energy carrier such as brown coal [4].

Besides the reduction of the investment costs and the increase of the power production, wind farm operators optimize structural integrity management (SIM) procedures to reduce the LCoE. Such optimizations are constrained by different rules and standards (e.g. requirements set out in Germany by the Bundesamt für Seeschifffahrt und Hydrographie (BSH) or in United Kingdom by the Department for Business, Energy & Industrial Strategy and the Marine Management Organisation). The challenge is to optimize the operation of an offshore wind farm including the SIM in compliance with the governing rules and standards.

In the existing literature, the overall costs related to the SIM are low in contrast to other costs such as the investment costs and the costs related to the turbine integrity management [5, 6]. Based on this information, the question is whether it is worthwhile to optimize the SIM for the support structures in an offshore wind farm to reduce the LCoE.

In this paper, a sensitivity analysis is performed to quantify the influence of the SIM on the LCoE of a generic offshore wind farm and to investigate the opportunity of upgrading/optimizing the SIM to reduce the LCoE (i.e., an optimization of the inspection and maintenance strategy as well as monitoring systems). To investigate the influence of the SIM on the LCoE, the operational expenditures are divided in a part related to the structures and a part related to the turbines. The LCoE is calculated on the basis of current scientific literature, in which the operational expenditures related to the support structures in an offshore

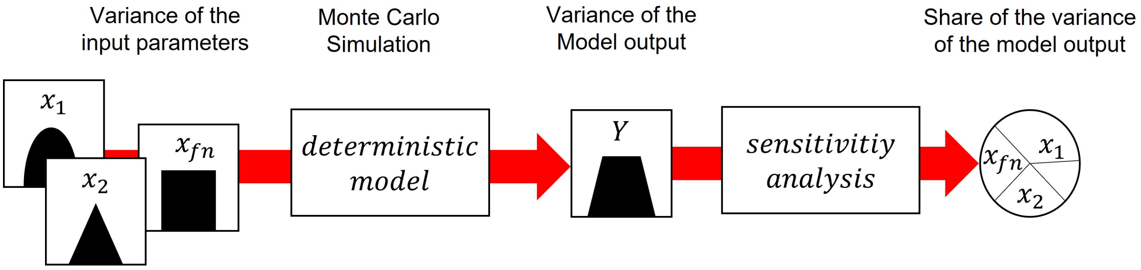

FIGURE 1. Illustration of a global sensitivity analysis, adapted from [5].

wind farm are determined based on the requirements defined by the BSH. To determine the effect of the SIM and other influencing parameters, the first order sensitivity index (Sobol index) is calculated based on a parametric model of the LCoE.

2. LEVELIZED COST OF ENERGY

The LCoE quantifies the average net costs for generating electricity with a certain type power plant. It is defined as the ratio between (a) the sum of the costs consisting of the capital expenditures (CAPEX) and accumulated operational expenditures (OPEX) and (b) the sum of the annual energy production (AEP) over the service life L (Equation 1) [6].

$$LCoE = \frac{CAPEX + \sum_{t=1}^{L} \frac{OPEX}{(1+i)^t}}{\sum_{t=1}^{L} \frac{AEP}{(1+i)^t}} \tag{1}$$

The CAPEX contain the investment costs of an offshore wind farm, while the OPEX include the costs related to the operating of the support structures and turbines including the costs for monitoring, inspection and maintenance. OPEX and AEP are discounted based on the discount rate i. The AEP of an offshore wind farm is computed as the product of the nominal (turbine) capacity nom_{cap}, the nominal capacity availability factor nom_{capava}, the turbine availability $turb_{avafac}$, the number of wind turbines n_{wt} and the feed in tariff $feed_{in}$ ((Equation 2) [7].

$$\begin{aligned} AEP = n_{wt} \cdot nom_{cap} \cdot 365.25 \cdot 24 \\ \cdot nom_{capava} \cdot tubr_{avafac} \cdot feed_{in} \end{aligned} \tag{2}$$

The capital expenditures are calculated in function of the number of wind turbines n_{wt} in a particular wind farm and the investment costs per wind turbine $turb_{invest}$ (Equation 4)

$$CAPEX = n_{wt} \cdot turb_{invest} \tag{3}$$

The operational expenditures depend on the number of wind turbines n_{wt} and the operational costs per wind turbine $turb_{operation}$ (Equation **??**).

$$OPEX = n_{wt} \cdot turb_{operation} \tag{4}$$

3. SENSITIVITY ANALYSIS

A sensitivity analysis provides information on how input parameters X and their uncertainties influence the output Y of a deterministic model. A distinction is made between local and global sensitivity analyses [5]. A local sensitivity analysis studies the influence of variability of the input parameters on the model output around a point x_0. Generally, the influence of small changes in input parameters on the model output is investigated. A global sensitivity analysis determines the influence of the input parameters by varying them over their entire domain. The basic procedure of a global sensitivity analysis is illustrated in Figure 1. The input parameters may have the same or different marginal probabilistic distributions. The variance of the model output Y depends on the variance of the input parameters and the relations implemented in the deterministic model. In a global sensitivity analysis, the share v_i of the variance of model output y that is caused by the input parameter x_i is determined.

A sensitivity analysis can pursue different goals [8, 9]:

- Robustness: Understanding the model's robustness with regard to the input parameters
- Ranking: Rank input factors according to their importance
- Screening: Identifying input factors with minor importance, which can be omitted
- Mapping: Identifying the areas of input parameters, which lead to extreme model outputs
- Decision support: Quantify the effect of decision variables on the model output.

In this contribution, the sensitivity analysis is performed to rank the parameters influencing the LCoE according to their importance. To this end, the variance-based sensitivity analysis is applied which defines an input parameter's importance in terms of its contribution to the variance of the model output $Var[Y] = Var[g(X)]$. In this approach, the influence of the uncertainty in an input parameter X_i on the variance $Var[Y]$ is quantified by a first order measure V_i (Equation 5) [9]

$$V_i = Var_{X_i}\{E_{X_{-i}}[g(X)|X_i]\} \tag{5}$$

Wind turbine	$CAPEX_{struc}$/k€/MW	$CAPEX_{turbine}$/k€/MW	Reference
4-A-14	677	2021	[10]
4-D-14	861	2131	[10]
8-A-14	689	1997	[10]
8-D-14	722	2180	[10]
6.1-MW Fixed-Bottom Offshore Wind Turbine	723	2823	[11]
Generic Offshore Wind Turbine	1065	2891	[12]

TABLE 1. CAPEX of different offshore wind turbines divided into a structural and a turbine part.

in which $E_{X_{-i}}\left[g\left(X\right)|X_i\right]$ is the expected value of $Y = g(X)$ with respect to all input variables except X_i, which is fixed. V_i is zero, if X_i has no effect on Y and the expected values is constant with regards to X_i. If X_i is the only random variable with an effect to the model output, V_i is equal to the full variance of the model output $Var[Y]$. The first order measure V_i can be estimated using a Monte Carlo Simulation, which results in n_{MCS} samples of the model output [9]. For every input parameter X_i, the sample pairs (X_i, Y) are ordered according to the value of X_i. The samples are divided into blocks of size n_b and the mean value μ_{Y_i} of each block is an estimate of $E_{X_{-i}}\left[g\left(X\right)|X_i\right]$. The variance of the block means μ_{Y_i} is an estimate of V_i. A more efficient way for determining the first order measure V_i is the Sobol sequence [13]. Based on V_i, the first order sensitivity index S_i can be computed as follows [14] (Equation 6).

$$S_i = \frac{V_i}{Var[g(X)]} = \frac{Var_{X_i}\{E_{X_{-i}}\left[g\left(X\right)|X_i\right]\}}{Var[g(X)]} \quad (6)$$

4. NUMERICAL STUDY

To study the influence of the structural integrity management on the LCoE, the capital and operational expenditures are divided into a part related to the structure and a part related the turbine (Equation 7 and 8).

$$CAPEX = n_{wt} \cdot (CAPEX_{struc} + CAPEX_{turbine}) \quad (7)$$

$$OPEX = n_{wt} \cdot (OPEX_{struc} + OPEX_{turbine}) \quad (8)$$

The capital expenditures $CAPEX_{struc}$ and $CAPEX_{turbine}$ for one offshore wind turbine are obtained from the data listed in Table 1. The values provided in Table 1 are normalized by the nominal turbine capacity.

Based on the data listed in Table 1, a range of $[677, 1065]$/k€/MW is assumed for the capital expenditures related to the structure $CAPEX_{struc}$, while the capital expenditures related to the turbine $CAPEX_{turbine}$ exhibit a range of $[1997, 2891]$/k€/MW.

The operational expenditures related to the structure are derived based on a study documented in [15]. The characteristics as well as the environmental and operational conditions of the wind farm considered in [15] are summarized in Table 2. Based on this wind farm, the operational expenditures are estimated for an inspection and monitoring strategy with three different settings (optimistic, average, pessimistic) [15]. The inspection and monitoring strategy is in accordance with the requirements defined by the BSH as summarized in Table 3.

According to the requirements set out by the BSH, general visual inspection (GVI) of the primary and secondary steelwork of the support structures in the wind farm above water is performed every year to provide a general overview on any obvious mechanical damage, fatigue or corrosion. Typically, such an inspection is performed by inspectors from a crew transfer vessel. In addition, 25% of the support structure are inspected using close visual inspection (CVI) and detailed visual inspection (DVI). The aim of CVI is to identify fatigue or corrosion and determine whether non-destructive testing (NDT) would be necessary to investigate the welded connections. In contrast to GVI, such an inspection is carried out closer to the support structure. According to [15], the objective of DVI is to determine the extent of detected damage. For this purpose. methods of non-destructive testing (NDT) may also be used.

Below water, the number of support structures considered for GVI is reduced to 25% every year, while the aim of obtaining a general overall overview on the condition of the support structures remains the same. However, the difference is that a remotely operated vehicle is used to perform the inspection. CVI below water is performed to identify corrosion or fatigue damage and to determine whether NDT would be necessary to inspect the structural components [15]. For this type of inspection, good environmental conditions and visibility as well as marine growth cleaning are required. DVI is used to determine the extent of detected damage using NDT methods [15]. The number of support structures inspected by CVI and DVI per

Characteristic	Unit	Value
Number of OWTs	–	100
Turbine capacity	MW	5
WF area	km^2	50
Average distance to port	Km	50
Average water depth	m	30
Foundation type	–	Monopile
Number of offshore substations	–	1
Average wind speed	m/s	10 (at hub height)
Tidal conditions	s	0.5 (HAT to LAT)
50-year wave	M	6.5
Current	m/s	1
Number of export cables	–	1

Table 2. Wind farm characteristics and environmental and operational conditions [15].

Activity		SHMS in 10% of WTs	Inspection Frequency during Service Life
Above Water	GVI of primary and secondary steelwork	100% every year	25
	CVI of primary and secondary steelwork	25% every year	6.25
	DVI of primary and secondary steelwork	25% every year	6.25
Seabed scour survey		100% the 2 first years and then 25% every year	7.75
Subsea marine growth survey		25% every year	6.25
Cathodic protection potential survey		100% the 2 first years and then 25% every year	7.75
CVI of the grouted connection		25% every year	6.25
Below Water	GVI of primary and secondary steelwork	25% every year	6.25
	CVI of primary and secondary steelwork	25% every year	6.25
	DVI of primary and secondary steelwork	25% every year	6.25

Table 3. Inspection strategy [GVI: general visual inspection; CVI: close visual inspection; DVI: detailed visual inspection] [15].

Boundary conditions	optimistic	average	pessimistic
$OPEX_{struc}$	1.2%	1.6%	1.9%
$OPEX_{turbine}$	98.8%	98.4%	98.1%

Table 4. Relative contribution of $OPEX_{turbine}$ and $OPEX_{struc}$ to the $OPEX$.

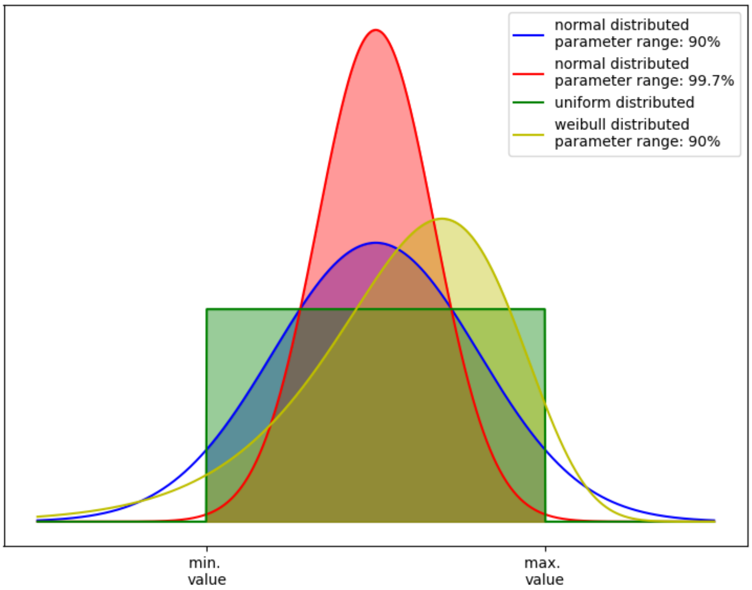

Figure 2. Illustration of the distribution types for a given value range defined in terms of the min. and max. value.

year below water is the same as the number of support structures inspected by CVI and DVI above water.

A seabed scour survey, a subsea marine growth survey and an inspection of the cathodic protection are performed for 100% of the support structures in the first two years. Thereafter, this inspect effort is reduced to 25% of the support structures in each year. The objective of the marine growth survey is to determine the coverage, thickness and type of marine growth on the support structures and sacrificial anodes to guide decisions on removing the marine growth. In a scour survey, the seabed around the support structures is inspected to monitor changes in the topology (local and global). An inspection of the cathodic protection determines if there is adequate global cathodic protection of the submerged part of the support structures.

According to the requirements defined by the BSH, continuous sensor-based monitoring systems (structural health monitoring systems and conditional monitoring systems) have to be installed on 10% of the wind turbines.

The operational expenditures related to the structures $OPEX_{struc}$ and turbines $OPEX_{turbine}$ relative to the OPEX are given in Table 1. These values are determined in [15] based on the inspection and monitoring scenario described above in conjunction with optimistic, average and pessimistic estimates of the associated costs.

From Table 4 it can be seen that the $OPEX_{struc}$ ranges between 1.2% to 1.9% of the overall OPEX. The accumulated discounted operational expenditures $\sum_{t=1}^{L} \frac{OPEX_{struc} + OPEX_{turbine}}{(1+i)^t}$ of an offshore wind farm correspond to approximately 25% of the total costs consisting of capital and operational expenditures [21]. To estimate the ranges of the absolute values (min./max. values) of $OPEX_{turbine}$ and $OPEX_{struc}$, a simple Monte Carlo simulation is performed. In this analysis, the CAPEX is modelled as a uniform distributed random variable. Furthermore, the service life and the discount rate are also modelled as uniform distributed random variables. In combination with the knowledge on the relative values of $OPEX_{turbine}$ and $OPEX_{struc}$ (modelled as uniform distributed random variables) (Table 4), the ranges of the absolute values of $OPEX_{turbine}$ and $OPEX_{struc}$ can be estimated. From this analysis it was found that the operational expenditures $OPEX_{turbine}$ exhibit a range of $[64, 135]$/k€/MW/year, while the operational expenditures $OPEX_{struc}$ are $[0.8, 2.6]$/k€/MW/year.

In the current case study, it is assumed that the service life L of the wind farms may be extended from 20 years up to 30 years [20].

The nominal capacity availability factor $nom_{cap\,ava}$ describes the ratio between the average power output of a wind turbine (usually one year) to its maximum output and exhibits a range of $[0.4, 0.5]$ [16]. This factor is affected by a variety of influencing factors and conditions including the windspeed.

The turbine availability factor $tubr_{ava\,fac}$ specifies the expected average availability over the service life. Considering only downtime the turbine itself. The factor accounts for the loss of energy associated with amount of time, when the turbine is not available to

Variable		Unit	Uniform distribution		Normal distribution			Ref.
			Lower bound	Upper bound	Mean value	Standard deviation (99.7%)	Standard deviation (90%)	
Number of wind turbines	n_{wt}		100	100	100	0	0	
Nominal capacity	nom_{cap}	[MW]	6	6	6	0	0	
Nominal capacity availability factor	$nom_{cap\,ava}$		0.4	0.5	0.45	0.02	0.03	[16]
Turbine availability factor	$turb_{ava\,fac}$		0.857	0.996	0.93	0.025	0.04	[17]
Feed in tariff	$feed_{in}$	[€/kWh]	0.14	0.16	0.15	0.003	0.006	[18]
Turbine invest: structure	$CAPEX_{struc}$	[k€/MW]	667	1065	871	70	118	Table 1
Turbine invest: turbine	$CAPEX_{turbine}$	[k€/MW]	1997	2891	2444	162	271	Table 1
operational expenditures: structure	$CAPEX_{struc}$	[k€/MW/year]	0.8	2.6	1.7	0.3	0.54	[5, 17]
operational expenditures: turbine part	$CAPEX_{turbine}$	[k€/MW/year]	64	135	99.5	12.2	21.6	[5, 17]
Discount rate	i		0.06	0.08	0.07	0.003	0.007	[19]
Service life	T	[year]	20	30	25	1.8	3	[20]

Table 5. Parameters of the probabilistic models applied in the sensitivity study.

produce energy, e.g. due to failure or maintenance. The availability of the turbine per year is in the range of $[0.857, 0.996]$ [17].

The feed in tariff $feed_{in}$ describes the state fixed remuneration for electricity to subsidize certain types of electricity production, e.g. electricity generated by offshore wind. It is in the range of $[0.14, 0.16]$/€/kWh for offshore wind [18]. The discount rate i is in the range of $[0.06, 0.0825]$/year for offshore wind in Germany [19].

Often, only the minimal and maximal value of the parameters are available in the literature, but not the distribution type. First, it is assumed that the parameters influencing the LCoE are normal distributed. The calculation of the sensitivity indexes is performed for two different standard deviations of the input parameters. It is assumed that the input parameter ranges account for 99.7% and 90% of the values, whereby both ranges are symmetric to the mean value. In addition, the sensitivity indexes are also calculated

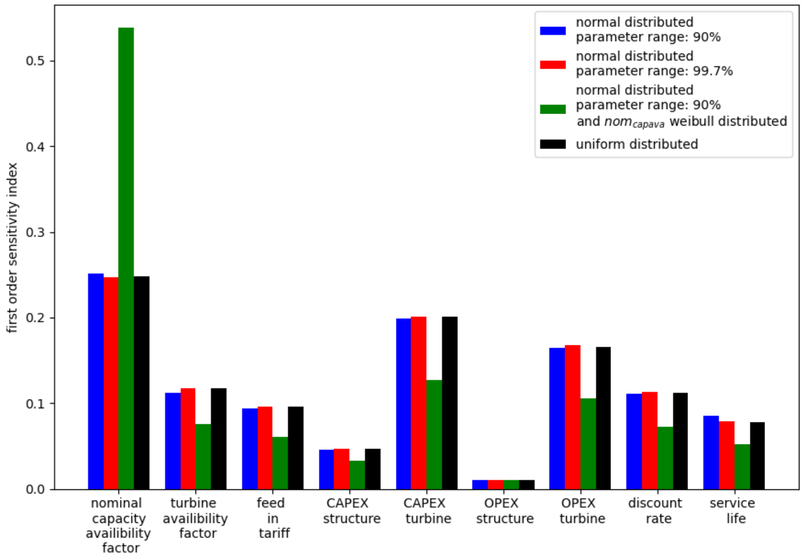

FIGURE 3. First order sensitivity indices of the parameters influencing the LCoE.

Parameter	First order sensitivity index			
	normal distributed parameter range: 90%	normal distributed parameter range: 99.7%	normal distributed parameter range: 90% and $nom_{cap\,ava}$ as Weibull distributed	uniform distributed
Nominal capacity availability factor	0.25	0.25	0.54	0.25
Turbine availability factor	0.11	0.12	0.08	0.12
Feed in tariff	0.09	0.09	0.06	0.09
capital expenditures: structure	0.04	0.05	0.03	0.05
capital expenditures: turbine	0.2	0.2	0.13	0.2
operational expenditures: structure	0.01	0.01	0.01	0.01
operational expenditures: turbine	0.16	0.17	0.11	0.16
Discount rate	0.11	0.11	0.07	0.11
Service life	0.09	0.08	0.05	0.08

TABLE 6. First order sensitivity indices of the different input parameters.

for uniform distributed input parameters (Figure 2). Moreover, in an additional calculation, the nominal capacity availability factor is modelled as a Weibull distributed random variable to reflect the large influence of the wind speed [22]. The parameters of the Weibull distribution are determined by assuming that 5% of the values are smaller than 0.4 (the lower value of the parameter range) and 5% are larger than 0.5 (the upper value of the parameter range). This results in a scale parameter of 0.47 and a shape parameter of 18.23.

max. value In the current case study, realizations of the turbine availability factor $tubr_{ava\,fac}$ which are larger than one are set to be equal to one. Note that, in the current example, the probability that the nominal capacity availability factor $nom_{cap\,ava}$ is smaller than zero or larger than one is zero regardless of whether it is modelled as a Weibull or normal distributed random variable.

In the calculation of the sensitivity indices, several simplifications are made. First, the input parameters are modelled as independent random variables. However, in reality dependence among some of the parameters exist, e.g. between the turbine availability factor and the costs due to maintenance / repair or investment costs. Another simplification is made in that the LCoE is determined without considering failure of the support structures, which are typically associated with large costs. This simplification is reflected in the model of the $OPEX_{struc}$, which describes only the inspection and monitoring costs without taking into account any failure costs. Further simplifications are made in the probabilistic modelling of the input parameters. As an example, the feed in tariff $feed_{in}$ and the discount rate i are modelled as time-invariant random variables even though they typically vary with time. The influence of the adopted simplifications has to be investigated in future research.

The parameters of the probabilistic models applied the sensitive analysis of the LCoE are provided in Table 5.

According to Figure 3 and Table 6, the indices depend on the distribution types. When modelling all the input parameters with the same distribution type (normal or uniform distributed), almost the same sensitivity indices are obtained. When modelling the nominal capacity availability factor as a Weibull distributed random variable, its influence increases, while the influence of the remaining parameters decreases. However, the trend in the relative importance of the parameters remains approximately the same.

It can be seen that the nominal capacity availability factor has the highest (first-order) sensitivity index, followed by the capital and operational expenditures related to the turbines. The discount rate, the turbine availability factor, and the feed in tariff have sensitivity indices in the same order of magnitude. The operational expenditures related to the support structures have always the smallest sensitivity index. The sensitivity index of the capital expenditures related to the support structure is smaller than the sensitivity index of the service life.

5. Summary and concluding remarks

In this contribution, a sensitivity analysis is performed to quantify the influence of the structural integrity management (SIM) on the levelized cost of energy (LCoE) of an offshore wind farm. The LCoE of a wind turbine/ farm describe the average net present cost, which arise from the conversion from wind to electrical power. To quantify the influence of the structural integrity management, the operational expenditures are divided into a part related to the structures and a part related to the turbines. The input parameters and their uncertainties are derived based on a literature study and characterize the actual situation/ data. The sensitivity analysis is performed for different probabilistic models of the influencing parameters. To quantify the relative influence of the parameters, their first order sensitivity index is calculated.

Based on the computed sensitivity index of the operational expenditures related to the support structures, it can be concluded that an optimization of the structural integrity management (SIM) aiming to reduce the operating costs may have negligible influence on the LCoE. A similar result has been obtained in a case study considering the effect of D-Strings on the LCoE of offshore wind turbine blades [23].

However, a significant influence of a service life extension on the LCoE is found. It can thus be concluded that the structural integrity management should be directed towards a service life extension. This may be achieved by means of monitoring the support structural integrity, i.e. by optimized monitoring systems to be utilized to optimized the time and location of measures such as repairs, which ensure the reliability of the wind turbine support structures beyond the original service life. It should be noted that a service life extension of the support structures makes only sense if the turbines also operate for the extended service life. This may be achieved by exploiting existing differences in the design service life of the turbines and the structure (e.g., 30 years for the turbines and 25 years for the structures) and/or turbine service life extension measures. In the latter case, the extension investments would need to be balanced with the monetary gain of extended production.

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