

Floating offshore wind - Economic and ecological challenges of a TLP solution



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ABSTRACT

Offshore wind farms will play an important role in supplying the increasing energy demand while considering ecological and economic aspects. Especially floating foundations which have a great potential for offshore wind farms in water depths between 40 m up to 200 m and more, will be a major factor. The objective of this paper is to focus on the design of a TLP substructure including the anchoring in the seabed by considering the economic and ecological aspects. One main focus is on economic challenges and the approaches for reduction of the investment costs and the Levelized Cost of Energy. A second focus is on the cumulative energy demand as well on the expected CO₂-emissions during the fabrication process.

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1. Introduction

Constant and high wind speeds as well as low wind turbulence enable high full load hours and thus increase the attractiveness of offshore wind farms far from the coast with regard to sustainable energy supply. Coastal offshore wind farms have a visual impact on coastal communities and the tourism sector and are prone to rejection in terms of aesthetics and noise pollution. However, at large distances from shore (greater than 30 km), the water depths in North Sea and Baltic Sea are vastly increasing. The construction of floating substructures for offshore wind turbines (in 60–1000 m water depth) offers significantly greater potential compared to fixed offshore wind turbines with regard to available areas for deployment [1]. The market for floating offshore wind turbines shows great potential worldwide [2].

Floating offshore wind farms far from the coast clearly leads to significantly higher investment expenditures compared to fixed offshore wind farms (see Fig. 1). There are also environmental impact aspects which make the construction of large wind farms using bottom-fixed foundations in the seabed considerably more difficult due to lengthy permitting processes.

Nevertheless, the aforementioned challenges do not stop floating substructure developers from further developing and establishing themselves in the market by addressing the Levelized Cost of Energy (LCOE) as key factor which is an important parameter for assessing the economics of energy systems [3]. For already realized offshore wind farms in Europe, the LCOE is currently between 7.3 €/ct/kWh and 14.2 €/ct/kWh [4]. It is thus higher than the LCOE of onshore wind energy or conventional generation technologies [4]. Other reports show that the LCOE will increase to 8.0 €/ct/kWh by using turbines with higher rated power. That is one of the main findings from the EU INNWIND project [5]. Questionnaire responses from experts as published by Wiser et al. [6], show that fixed and floating offshore wind solutions will reach the same LCOE in the future, i.e. by 2030. All these reports assume one major fact to bring down the LCOE: a reduction of required investment costs for floating solutions is needed.

The necessity to reduce investment costs for floating offshore wind turbines and thus to optimize LCOE are at the core of possible approaches for an optimization along the entire life cycle of an offshore wind farm in general, and by using a TLP as presented in the following. For this purpose, the floating foundations are briefly outlined and the chosen TLP design is explained in more detail. Subsequently, the calculation methods for determining the LCOE are presented and the investment costs of floating and fixed

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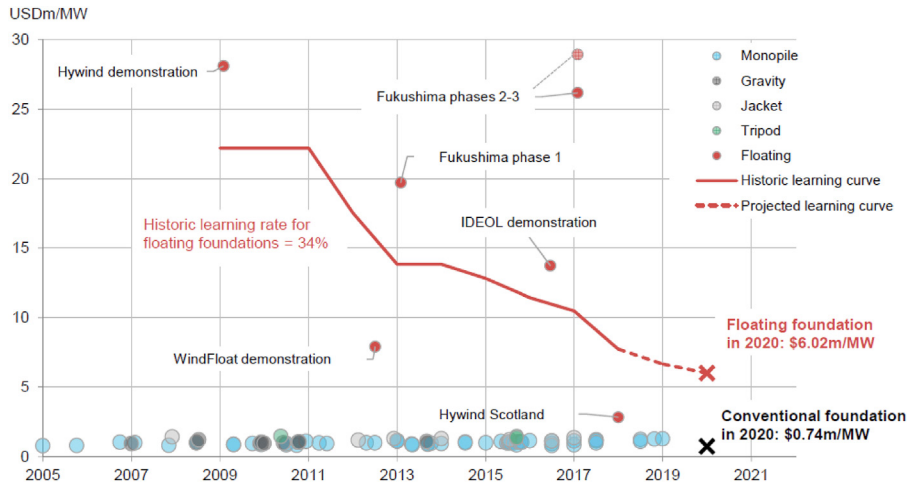


Fig. 1. Cost comparison of fixed and floating foundation concepts [3].

foundations are compared. Furthermore, the cumulative energy demand and the expected CO₂ emissions during the production process are discussed because this is one additional topic to be addressed by the developers, based on the requirements of regulatory entities such as the EU. In addition, the starting points for optimization of the investment costs are described using the example of the TLP developed by GICON®, and the LCOE is calculated. This is followed by presenting the sensitivity analyses and optimizing and evaluating the LCOE.

2. State of the art and calculation methods

2.1. Short technical overview

Floating substructures are segmented into semi-submersible, Spar-Buoy and TLP concepts [7]. They are anchored to the seabed with ropes or chains. The foundation concept selection is determined by technical, economic and ecological boundary conditions. There are currently various concepts of floating substructure solutions for offshore wind turbines, which can be segmented according to their type of stabilization concept. According to Butterfield et al. [8], there are ballast-stabilized, buoyancy-

stabilized and mooring line-stabilized foundation concepts (see Fig. 2, on the left). The chosen TLP is an example of a tension-leg-platform (see Fig. 2, on the right), combining buoyancy and tension based stabilization. In difference to classical TLP concepts ([9–13]), this TLP has floating stability for the transport phase from the assembling site to the offshore site without requiring additional buoyancy bodies [14].

In the context of economic feasibility studies, a TLP designed by the company GICON® and partners is presented at this point. This tension leg platform is a steel structure with buoyancy components and vertical and inclined pre-tensioned anchoring elements. Four air-filled buoyancy bodies, designed as vertical cylinders, are arranged at the corners of a square base and connected to each other via horizontal steel pipe systems. Centrally above the buoyancy bodies, vertical steel pipes are arranged which penetrate the water surface and connect the central connection transition piece over four box girders. This TLP including mounted tower and turbine can be towed floating to the wind farm ([14] [15]). In addition, in Fig. 2, a gravity anchor is shown to which the anchoring elements can be attached. The use of this gravity anchor eliminates costly and expensive pile driving. The last two aspects - the floating transport of the fully assembled TLP to the wind farm and the use of the

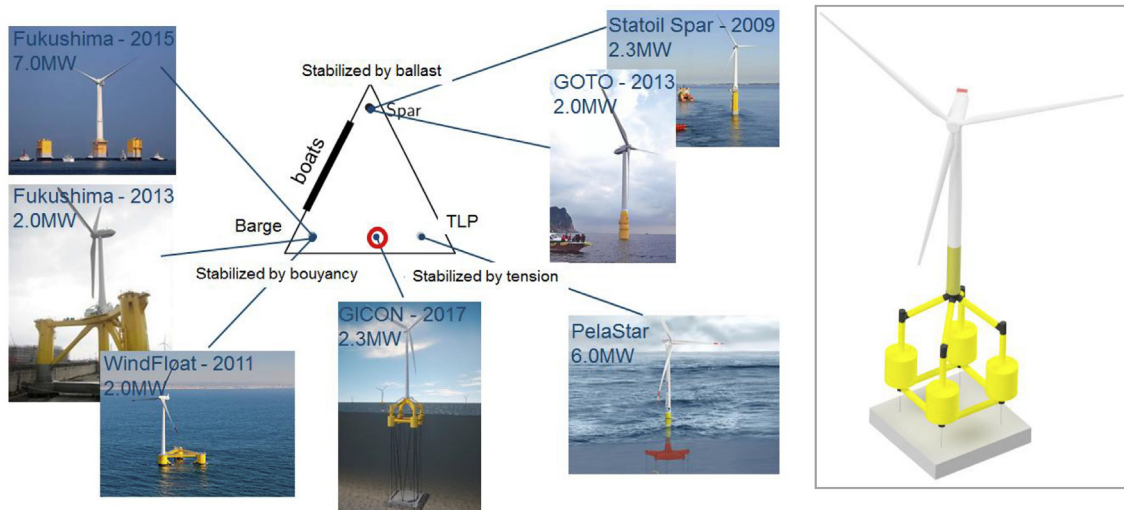


Fig. 2. Left: Floating substructure concepts with classification in the stability triangle (Source: based on Butterfield et al. [8]); right: chosen TLP.

heavyweight anchor - represent a unique characteristic for the chosen platform example and offers great potential for reducing LCOE.

2.2. Levelized Cost of Energy (LCOE)

The capital expenditure for offshore wind turbines is exceptionally high and, according to James and Ros [16], averages around 2700 €/kW. CAPEX costs are mainly determined by turbine, substructure and anchoring technology. A detailed cost breakdown of an offshore wind-turbine-project is important for calculating the life cycle costs (LCC) and the LCOE according to their respective methods. These costs can be separated into research and development, fabrication and construction, operation & maintenance and decommissioning.

LCC describes the entire costs of a project over its entire service lifetime. A comprehensive consideration of all costs incurred and the calculation of the LCC are essential to predict the profitability of a project as well as to compare alternative investments and make decisions regarding their use.

The financial attractiveness of an offshore wind farm project is defined by the LCOE amount. According to Hobohm et al. [17], the costs of different generation technologies (wind versus photovoltaics) or the costs of different designs of a generation technology (fixed versus floating foundation) can be compared with one another using the LCOE method. The LCOE describes the costs that are required to generate 1 kW hour of electricity. The LCOE (see equation (1) based on Valverde et al. [18]) considers the initial capital expenditures (CAPEX) as well as all annual operating expenditures (OPEX) and the annual generated electricity (EP_{NET}) incurred over the total project lifetime.

$$LCOE = \frac{CAPEX + \sum_{t=1}^n \frac{OPEX}{(1+WACC)^t}}{\sum_{t=1}^n \frac{EP_{NET}}{(1+WACC)^t}} \quad (1)$$

In this equation (1), WACC stands for the weighted average cost of capital. It is determined among other things by the existing risk of a project and is made up of costs of equity and borrowing costs and the respective yields. The WACC is usually used in real terms, taking into account inflation. According to Wiser et al. [19], an annual inflation rate of about 2% is assumed.

CAPEX describes the cost incurred to purchase longer-term assets such as business equipment, machinery or real estate. With regard to an offshore wind farm, there are costs for tower and turbines, substructures and the project integrated substation. The investment cost also consists of costs for certification and

permitting, planning and development, technology related costs, grid connection, site development, assembly and commissioning, transport, reserves for project risk, unforeseen expenses and eventualities, other costs of financing and investment and provisions for decommissioning and dismantling. In Fig. 3, the individual investment costs are shown as a percentage of total investments as a function of the cost structure.

In addition to CAPEX costs and the achievable energy production, OPEX is the most important factor influencing the operation of an offshore wind farm. OPEX describes the ongoing cost for running operation & maintenance (O&M) of a project. This includes inspection, repair or replacement of wearing parts to maintain and extend the plant operation. Of particular importance for operating costs are costs for O&M. Therefore, the main objective is the reduction of this cost factor.

2.3. Cumulative energy demand and CO₂ emissions

In addition to LCOE, CO₂ emissions and cumulative energy consumption also play a key role in evaluating a technology both economically and ecologically.

The Association of German Engineers (VDI) (Verein Deutscher Ingenieure) developed Guideline 'VDI-4600 on cumulative energy demand' (CED). CED is the sum of the primary energy-assessed cost, which arises in connection with production, use and disposal of an economic good that can be assigned. Both products and services are regarded as economic goods. The formula for the CED is:

$$CED = CED_F + CED_O + CED_R \quad (2)$$

The CED sum consists of the subtotals for cumulative energy demand for fabrication (CED_F), cumulative energy demand for operation (CED_O) and cumulative energy demand for recycling (CED_R), whereby the sub-totals must indicate secondary stages.

The CED_F includes all primary energy-assessed energy expenditures, which are required for the production of the object or the service itself, as well as for the production, processing, production and disposal of the production, auxiliary and operating materials and means of transport, including transport expenses. The CED_O is defined by the primary energy-assessed expenses that occur during operation or use of the object or service. The sum includes operating energy consumption, production and disposal of consumables, auxiliary materials and operating resources which are essential for operation and maintenance, including all energy expenditures for transport. The CED_R is assessed by the primary energy expenditures that arise during the disposal of an object or parts thereof. Energy expenditure for the disposal itself, for

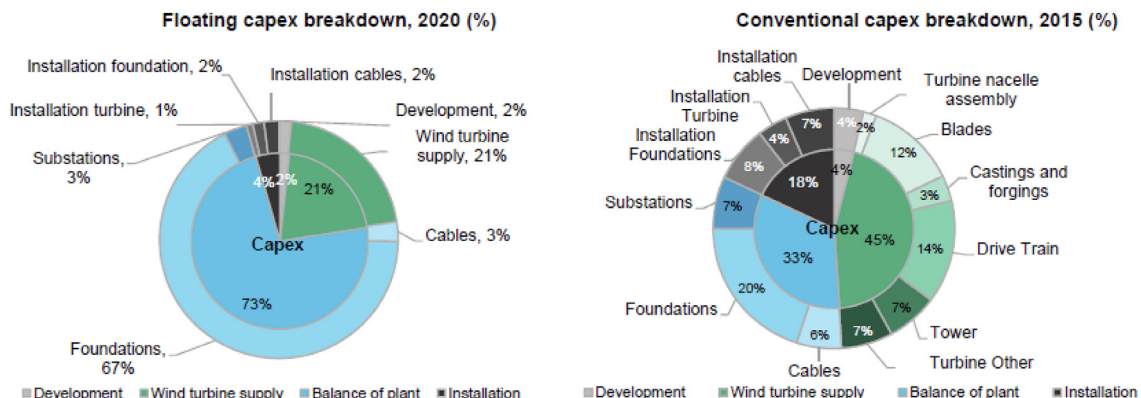


Fig. 3. Capex breakdown for floating and fixed offshore foundation [3].

production and disposal of auxiliary and operational resources required for the disposal, including all transport costs, are included.

According to the definition as per guideline VDI-4600, the balance sheet limit for the CED determination of the considered commodity extends from the raw material in the investment to the final disposal or deposition. All materials and substances must be taken into account as well as the diffuse exchange of substances with air, water and soil. In order to meet this complex requirement, an important basis for the CED calculation is the clear definition of the balancing area. This means that transgressive material and energy flows are to be precisely defined and quantified.

The CO₂ emissions compilation was performed in the same way as for the CED balance. The procedure is the same and was first carried out by means of a stock of materials. This is followed by the accounting for the three lifecycle phases of fabrication, operation and recycling (CO_{2F}, CO_{2O}, CO_{2R}). These are then summarized and the results of the various systems are allocated per 1 MW for comparison.

In parallel to the CED balance, the CO₂ emissions were separated into assemblies and other expenditures. The allocation of the respective expenditures for the CO₂ emissions CO_{2F}, CO_{2O} and CO_{2R} are comparable. The value for CO_{2O} and the recycling value for CO_{2R} were set to zero as the value for the CO_{2O} because these values are very small for the operation of the plant.

The following is a sample balance for cumulative energy demand and CO₂ emissions.

3. Results: LCOE for a TLP as an example

3.1. Assumptions

Based on the technical and economic fundamentals for offshore wind turbines, the interfaces for cost reductions are shown by variables in Fig. 4. The reduction of individual cost variables has

different impacts on the LCOE amount. Sensitivity analyses show how sensitively the LCOE reacts to variation of the individual costs.

In the following, the presented assumptions and explanations made are related to the GICON[®]-TLP-project. The assumptions are based on a wind farm consisting of 80 6 MW turbines and thus as total capacity of 480 MW. This also describes a serial production effect that can reduce the CAPEX costs. The site conditions of the wind farm are additionally described by a water depth of 30 m and a distance from shore of 40 km. The lifetime for this project is 20 years. The GICON[®]-TLP is completely assembled in the harbor and is towed floating to the wind farm. The anchoring process can be carried out using the gravity anchor system as shown in Fig. 2 (right). The investment costs for this project are shown in Table 1 and are based on the estimated assumptions and restrictions.

Fig. 5 is based on Table 1 and demonstrates that the costs of the turbine (43.4%) as well as the costs for fabrication and installation of the TLP (in sum equal to 33.4%) represent the largest proportionate costs. In addition, the costs for grid connection and the internal substation are about 15.5%.

The LCOE calculations are based on further assumptions. The availability factor of the WTG is 76%. Gross full load hours in terms of 5.193 MWh/MW are assumed. The OPEX costs are described using the charge cost rate of 24.30 €/MWh. The inflation-based increase in operating costs is about 2.0%. The WACC are estimated at 6.17%. Based on these assumptions, the LCOE for the GICON[®]-TLP project is calculated at 9.52 €/ct/kWh. This is the initial value for all further considerations. The LCOE is optimized based on this value.

Fig. 6 shows the impact of the individual CAPEX and OPEX costs related to the LCOE. The results are based on the implementation and expansion of the cost structure. This figure shows that the investment for the turbine (30.7%), the costs for the TLP including the gravity anchor (11.4%) as well as the installation costs (9.9%) and the costs for O&M (29.3%) decisively determine the LCOE with a total share of 81.2%.

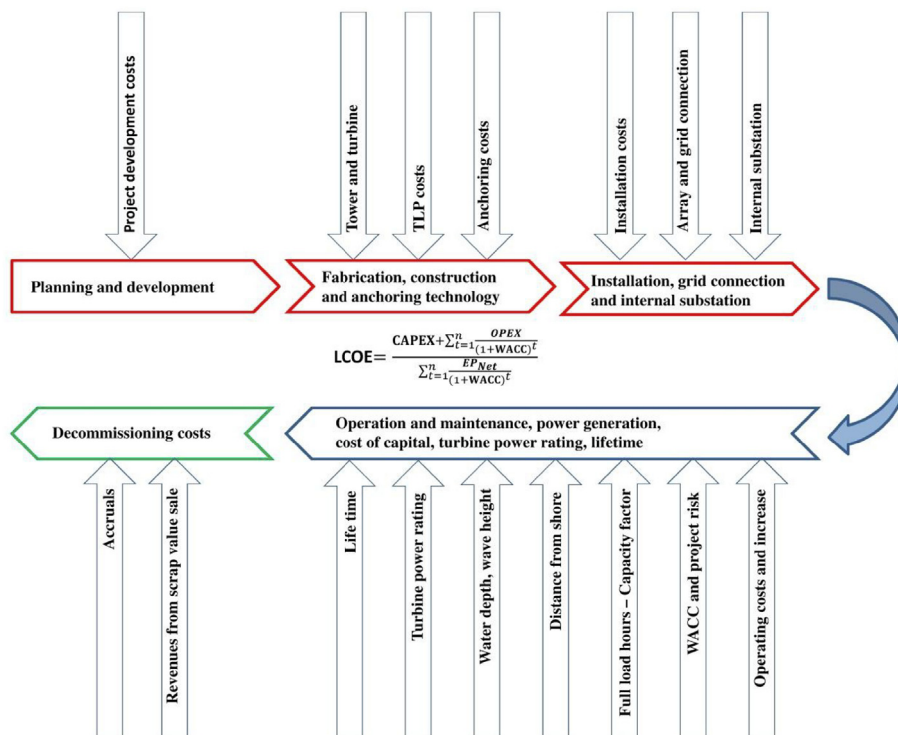


Fig. 4. Approaches to cost optimization in the project phases of an offshore wind farm.

Table 1
TLP basic costs for calculating the LCOE (based on Adam et al. [21]).

CAPEX costs for the TLP (second generation)		6.0 MW-WTG
1	Cost for project development	€ 375,000
	Foundation inspection	€ 250,200
	Environmental impact assessment/permitting process	€ 62,400
	Certification, financing, design studies, expert opinions	€ 62,400
2	Cost of plant and foundation	€ 12,893,994
	Wind turbine generator	€ 7,800,000
	Tower	€ 786,000
	Structural design (TLP)	€ 3,480,000
	Anchoring (ropes, connectors, strand lifters, ...)	€ 827,994
3	Installation costs	€ 3,100,002
	Transport and lowering	€ 1,000,002
	Anchoring system	€ 700,002
	Cable purchase	€ 300,000
	Cable installation and grid connection	€ 1,099,998
4	Internal substation	€ 1,392,000
5	Decommissioning costs minus scrap value	€ 215,000
	Dismantling of TLP	€ 300,000
	Return transport	€ 165,000
	Revenues from scrap sale	€ -250,000
Total costs TLP (CAPEX)		€ 17,975,996

3.2. Sensitivity analysis methods

In a first step, all potential cost variables are sifted using the *screening method*. Table 1 is used for a first variable selection. In relation to this table, twelve cost variables X_i ($i = 1 \dots 12$) are selected. Subsequently, a variable analysis is performed according

to the LCOE (see formula (1)). This investigation leads to the inclusion of four further variables X_i ($i = 13 \dots 16$). The broader view focuses on the variables related to the costs of operating and energy production. This results in the inclusion of five additional variables X_i ($i = 17 \dots 21$) as shown in Table 2. Furthermore, these 21 variables are distinguished in terms of their influence on external and technological variables. External variables can be influenced marginally; technological variables can be significantly influenced. This delineation is decisive for the evaluation and selection of the variables for further calculations.

In the second step, *local sensitivity analyses* are carried out for these variables in fixed interval boundaries. The variable dependencies are disregarded (*ceteris-paribus*). The base value is determined by the cost structure according to Adam et al. [21]. A sampling is performed in the entire interval. The upper and lower interval limits are on the one hand determined on the basis of literature and on the other hand on the basis of empirical investigations. Detailed in-house empirical investigations were made available for the investment costs of the GICON®-TLP-structure (X_6), for the real cost of capital (X_{15}), for water depth (X_{19}), for wave height (X_{20}) and for the life time (X_{21}).

From this variety of variables, six variables for the *global sensitivity analyses* are selected based on selection criteria. In this third step, these six variables are examined for their global sensitivity, taking the correlations into account. To describe their dependencies, various direct and indirect constellations are examined and evaluated.

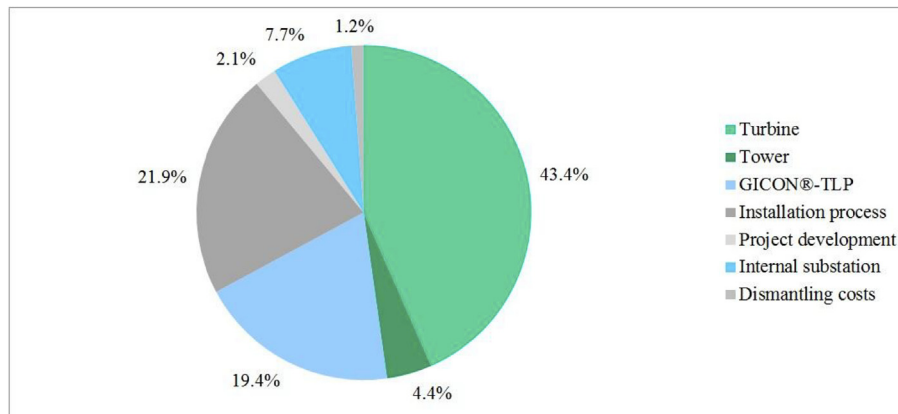


Fig. 5. Floating CAPEX breakdown for the TLP.

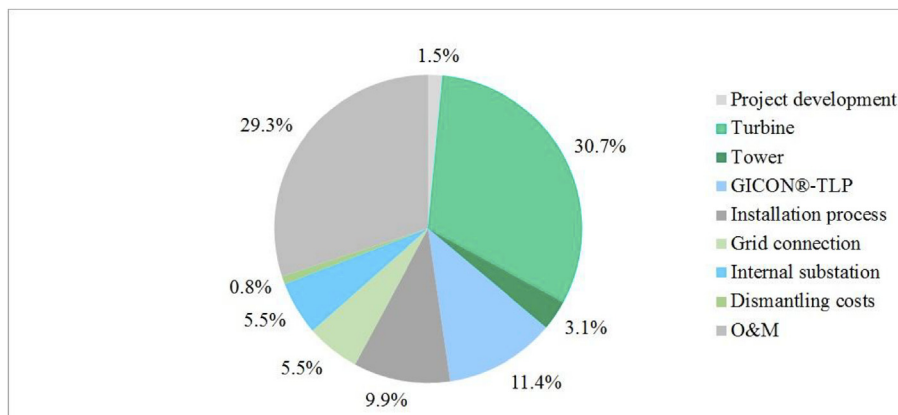


Fig. 6. LCOE Percentage breakdown according to the TLP.

3.3. Local sensitivity analysis results

Variable (X_1) describes all total investment costs. It is only for a first rough overview. This variable (X_1) is described below by the other variables and therefore not further separately investigated.

In Fig. 7, the results of the 20 examined input variables are plotted in a sensitivity diagram for a better overview. The extent of the sensitivity is illustrated by the slope of the individual functions. If the increase m_i is large, then the influence of the input variables on the LCOE is also large. The six variables with the greatest influence are additionally marked with a gray filled circle. The representation of the individual functions in Fig. 7 takes place in the percentage interval of $\pm 60\%$. The intersection of all functions is at the base value with $100\% = 9.52 \text{ €ct/kWh}$. This intersection divides the graphic into four quadrants. The LCOE reduction potential is illustrated in quadrants ③ and ④. It can be seen that the variables for TLP (X_6) investment costs, operating costs (X_9), revenue proceeds (X_{13}), full load hours ($X_{14, b}$) as well as WACC (X_{15}) and generator power rate (X_{17}) are distinctly different from the other variables. The revenue proceeds are described by the steel scrap sale of the GICON®-TLP, the resale of tower and turbine as well as cable scrap at the end of the lifetime.

Note: It should be noted that the selection of significant variables must be based on subjective decisions. In column II of Table 2, the increases of the sensitivity functions and the percentage deviations in the LCOE are plotted with a 10% variation of the input variables. Furthermore, the entire LCOE interval range (column III) and the maximum possible LCOE savings (column IV) with respect to the base value are shown in Table 2. Thus, the six characteristic

variables for recording in the global sensitivity analysis are determined.

In general, it can be postulated that the results of the local sensitivity analysis can also be applied to other substructure concepts such as semisubmersible or spar buoy. This is possible due to the approach of variables which are generally used for offshore wind turbines. Only the interval ranges have to be set to the respective substructure concept.

3.4. Global sensitivity analysis results

For the global sensitivity analysis, three possible constellations as listed in Table 3 are used based on the variables selected. Direct and indirect variable dependencies are implemented within the program. These include, for example, correlations between generator power rate and full load hours and between full load hours and operating costs.

Finally, Table 4 summarizes the minimum and maximum LCOE value for the three universally performed sensitivity analyses.

In the following LCOE evaluation is performed as an example for constellation K_2 . Constellation K_2 considers the relationships of the following variables: investment costs TLP (X_6), operating costs (X_9), revenue proceeds (X_{13}), full load hours (X_{14}), weighted average cost of capital (X_{15}) and generator power rate (X_{17}) for the global sensitivity analysis. The correlations between operating costs, full load hours and generator power rate are taken into account by internal programming in Excel®. This constellation produces 12,584 possible combinations (see Fig. 8). The comparative base value of 9.52 €ct/kWh is marked by the gray column. There are 6160

Table 2
Results of the local sensitivity analysis.

I		II		III	IV
Sensitivity variables for local sensitivity analysis		Variation of the variable $\pm 10\%$		Interval range for LCOE	Maximum reduction for LCOE*
E = external variable		%		€ct/kWh	€ct/kWh
T = technological variable					
$X_1^{E,T}$	Total investment costs	(-)	-7.14	7.29–11.78	2.23
X_2^T	Project development costs	(-)	-0.11	9.41–9.67	0.11
X_3^E	Turbine investment costs	(-)	-3.05	8.96–10.09	0.56
X_4^E	Tower investment costs	(-)	-0.21	9.38–9.67	0.14
X_5^E	Investment costs for anchoring	(-)	-0.32	9.37–9.68	0.15
X_6^E	Investment costs for the TLP	(-)	-1.37	8.94–9.90	0.58
X_7^E	Installation cost for anchoring process	(-)	-0.63	9.02–10.16	0.50
$X_8^{E,T}$	Cable and grid connection costs	(-)	-0.53	9.20–9.85	0.32
X_9^E	Operating costs	(-)	-2.84	7.88–11.17	1.64
X_{10}^T	Annual increase in operating costs	(-)	-0.42	9.30–9.78	0.22
$X_{11}^{E,T}$	Investment costs for internal substation	(-)	-0.53	9.32–9.73	0.20
X_{12}^T	Decommissioning costs	(-)	-0.11	9.46–9.61	0.06
$X_{13,a}^E$	Revenues from steel scrap sale	(+)	-0.11	9.48–9.57	0.04
$X_{13,b}^E$	Revenues from cable scrap sale	(+)	-6.73	9.41–9.52	0.11
$X_{13,c}^E$	Revenues from sale of tower and turbine	(+)	-6.73	8.88–9.52	0.64
X_{13}^E	Total revenues	(+)	-6.73	8.72–9.57	0.80
$X_{14,a}^E$	Wind speed	(-)	+7.74	9.15–11.74	0.37
		(+)	-5.28		
$X_{14,b}^E$	Full load hours	(-)	+7.86	8.19–11.78	1.33
		(+)	-6.39		
$X_{15}^{E,T}$	Weighted average cost of capital	(-)	-3.59	8.21–10.99	1.31
X_{16}^E	Coastal distance	(-)	-0.67	9.36–10.37	0.16
		(+)	+0.61		
X_{17}^E	Generator power	(-)	+7.08	6.92–17.41	2.60
		(+)	-6.01		
X_{18}^E	Costs for project risk	(-)	+0.74	9.52–9.97	0.00
X_{19}^E	Water depth	(-)	-0.13	9.48–12.64	0.04
		(+)	+0.19		
X_{20}^E	Wave height	(+)	+0.05	9.52–9.58	0.00
X_{21}^E	Lifetime	(+)	+2.54	8.99–9.52	0.53

* ... according to base value.

(-)/(+) ... reduction/increase of variable X_i .

-/+ ... reduction/increase in the LCOE.

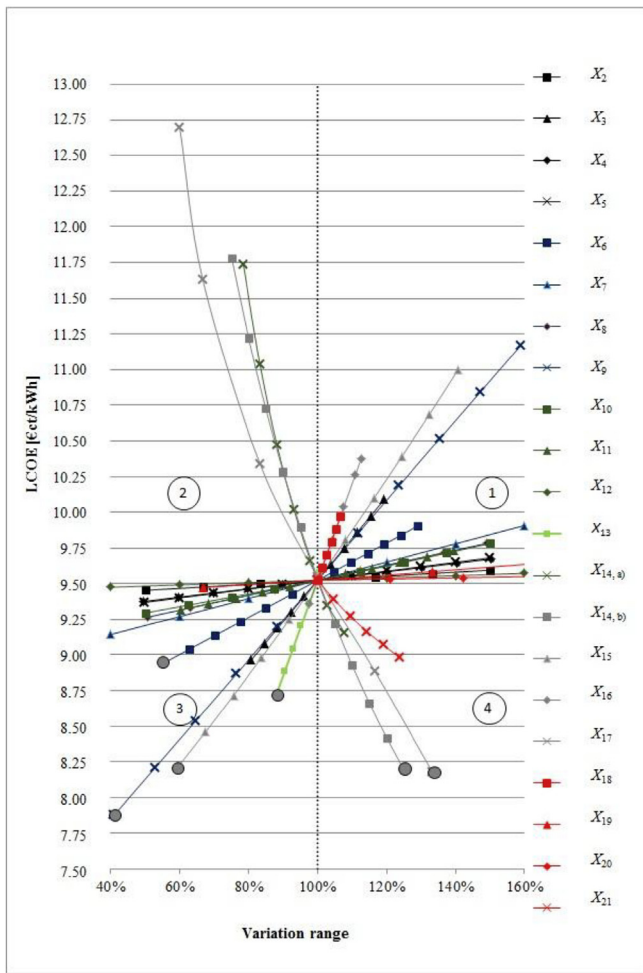


Fig. 7. LCOE as a function of the variables examined - local sensitivity.

possible combinations to the left of the comparative base value which show the LCOE reduction in green color. To the right of the comparative base value are 6424 combinations with higher LCOE, marked in red color. In addition, the cumulative number of possible combinations is shown in the form of an additional line.

In Table 5 and Fig. 8, the LCOE frequencies are plotted over the class division.

The diagram (see Fig. 9) represents the LCOE for the selected constellation K_2 as a function of a parameter set. In addition, in this diagram the color green has been used for more favorable LCOE and the color red for less favorable LCOE. The values between 10.0 €/kWh and 12.0 €/kWh describe the currently available or predicted LCOE in the offshore market and are shown transparently for

Table 3
Constellation possibilities K_i for global sensitivity analysis.

Constellation	Variables for global sensitivity analysis						Remarks
	Investment costs for TLP	Operating costs	Revenues	Full load hours	Weighted average cost of capital	Generator power rate	
K_1	X_6	(X_9)	X_{13}	X_{14}	X_{15}	/	(X_9) are determined by full load hours
K_2	X_6	(X_9)	X_{13}	(X_{14})	X_{15}	X_{17}	(X_9) and (X_{14}) are determined by generator power
K_3	X_6	(X_9)	/	(X_{14})	X_{15}	X_{17}	(X_9) and (X_{14}) are determined by generator power

* ... constant value.
/ ... no recording of the variable.
(value in brackets) ... direct dependency programmed.

Table 4
Minimum and maximum LCOE for the selected three constellations.

	Constellation K_1	Constellation K_2	Constellation K_3
LCOE _{min}	6.82 €/ct/kWh	LCOE _{min} 6.63 €/ct/kWh	LCOE _{min} 7.11 €/ct/kWh
LCOE _{max}	12.86 €/ct/kWh	LCOE _{max} 21.49 €/ct/kWh	LCOE _{max} 21.49 €/ct/kWh

better illustration. The calculated LCOE is between 6.63 €/ct/kWh and 21.49 €/ct/kWh.

Fig. 10 is another way of interpreting the results. In this figure diagram, the significant parameter combinations of the constellation K_2 can be read. On the first horizontal axis, the investment costs for the TLP (X_6) and the scrap sale revenues (X_{13}) are plotted. On the second horizontal axis, the weighted average cost of capital (X_{15}) and the full load hours (X_{14}) are illustrated. The third axis is perpendicular to the image plane and shows the LCOE level. Reductions in LCOE in accordance with the base value are mainly achievable in the upper areas of the graphic with appropriate parameter selection. Reductions in LCOE to below 7.0 €/ct/kWh are possible (see Fig. 11).

The dependency relationships between full load hours (X_{14}) and operating cost (X_9) are presented in full so that this constellation is subject to realistic assumptions. A reduction in investments costs for the GICON[®]-TLP (X_6) up to 500 k€/MW and a reduction of the WACC (X_{15}) up to 5.66% are likely. The full load hours (X_{14}) can also achieve significantly higher values than previously assumed. High revenue proceeds (X_{13}) from the sale of the old plant and the steel scrap are also reasonable. The constellation (K_2) thus represents an important scenario for the LCOE reduction for the GICON[®]-TLP. Fig. 10 can be also interpreted as a kind of 'reading rule'. The blue arrows mark a possible constellation of four input variables by showing the LCOE at less than 9.0 €/ct/kWh. Table 6 shows the individual variables with their initial values.

This type of 'reading rule' can also be applied to alternative fixed and floating foundation concepts. Only the variables in their interval limits and the dependencies have to be changed. This can be a high-quality tool for different companies.

4. Results: cumulative energy demand and CO2 emissions for the TLP example

For the selected example of the GICON-TLP, three different substructure types are examined. The first type is a steel-concrete structure ([20,21]) with cast steel nodes (Variant A). The second type is a structure of steel-reinforced concrete ([20,21]) with welded steel nodes (Variant B). The third type is a steel structure [22] (Variant C). All substructures are designed for a 6 MW WTG [23].

4.1. Cumulative energy demand

The sub-totals (fabrication, operation, recycling) for the three variants are explained in more detail below. Each total is

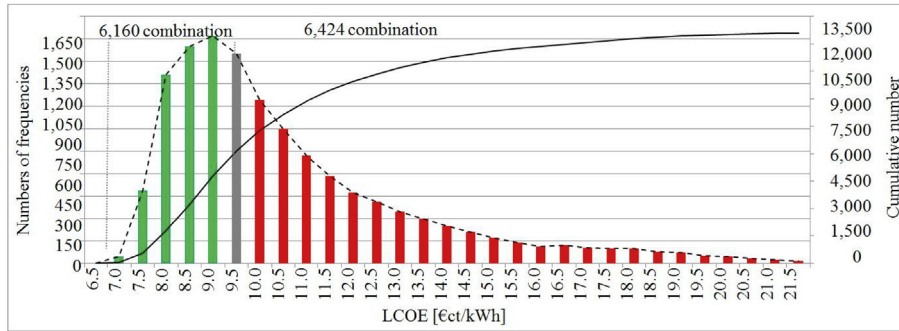


Fig. 8. Frequency distribution of the LCOE for the constellation K2.

Table 5
Representation of the classes and frequency distribution for the constellation K2.

Classes [€/ct/kWh]	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
Frequencies [-]	47	486	1258	1450	1520	1399	1093	897	719	585	47
Classes [€/ct/kWh]	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	12.0
Frequencies [-]	473	411	346	295	250	208	171	138	111	120	473
Classes [€/ct/kWh]	17.0	17.5	18.0	18.5	19.0	19.5	20.0	20.5	21.0	21.5	17.0
Frequencies [-]	102	99	97	78	70	51	45	31	21	13	102

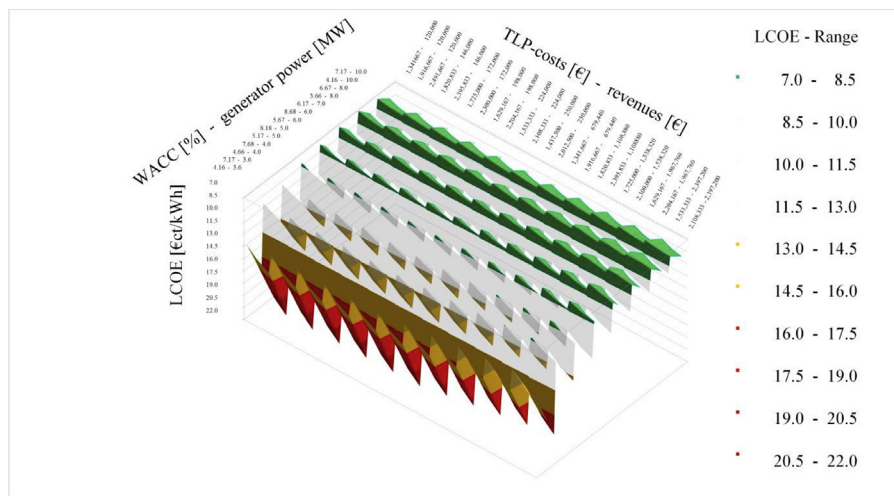


Fig. 9. Dependence of the LCOE on the constellation K2 (isometry).

subdivided into assemblies that consist of the TLP components as well as other expenses. In the CED_F of the subassemblies, the energy expenditures for material production, production and/or processing and transport of the semi-finished products to the assembly site are included. The CED_O was recorded with zero due to the small contribution. CED_R 's accounting categories include decommissioning and recycling. Other expenses include any expenses not attributable to the individual sub-assemblies. These are both the costs of production and disposal. All costs during the fabrication phase such as corrosion protection expenses, the entire equipment use at the shipyard (e.g. crushing or heavy load transporters), the equipment's electricity demand (e.g. welding equipment or generators) and transportation to the installation port as well as construction expenses are allocated to the total TLP costs. The costs to be included in the disposal phase comprise only the decommissioning at sea, return transport from site to port and the dismantling. The return transport and the decommissioning at sea are of the same order of magnitude as the transport operation and

the installation in the installation phase. The disassembly on land is calculated at 50% of the installation effort.

There are hardly any differences between variants A and B. However, the all-steel substructure shows a significantly higher CED. This is due in particular to the CED-intensive welding work for the respective TLP components, including all reinforcements.

4.2. CO₂ emissions

The CO₂ emissions were determined in parallel with the determination of the energy consumption. The procedure is not different.

Fig. 12 shows that Variant A has the lowest CO₂ emissions with just under 395 t/MW. Variant B is slightly above the value of Variant A at around 433 t/MW. Variant C has the highest CO₂ emissions at 688 t/MW.

When comparing all variants by referring to the CO₂ emissions of the individual expenses per 1 MW, it becomes clear that the

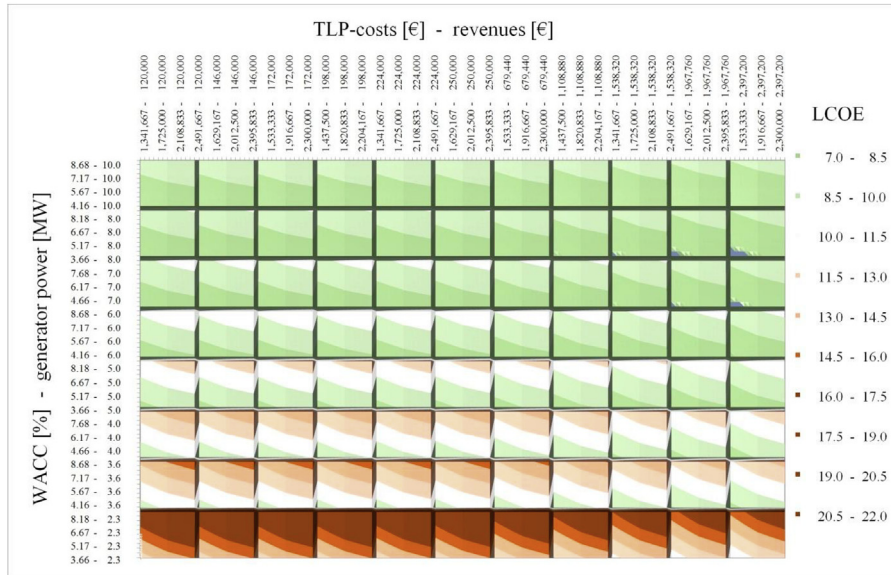


Fig. 10. Dependence of the LCOE on the constellation K2 (ground plan).

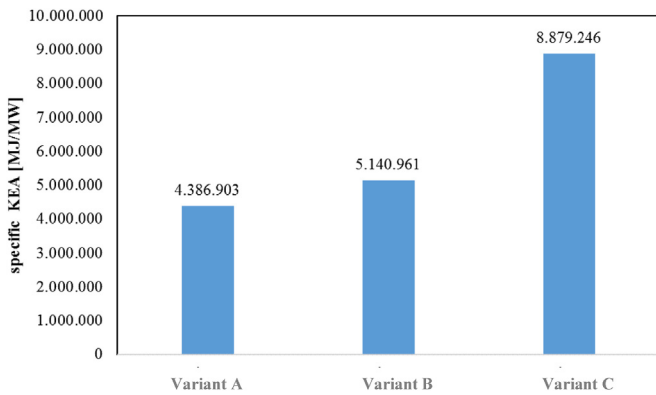


Fig. 11. Comparison of CED totals for variant A, B and C per 1 MW.

Table 6
Individual variables with their initial values.

Variable	Value
X_6 TLP-costs	500,000 €/MW
X_{13} Revenues	approximately 1,500,000 €
X_{15} WACC	approximately 6.17%
X_{17} Generator power	6.0 MW

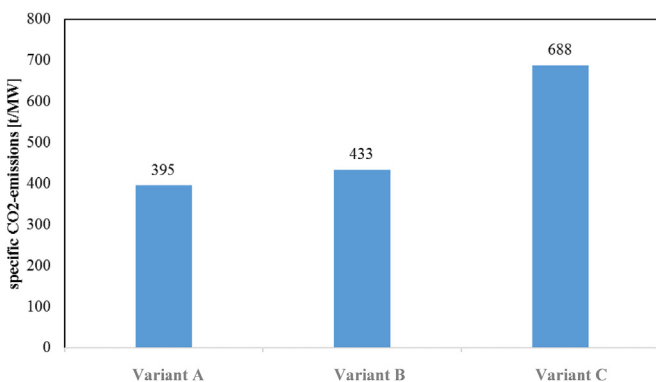


Fig. 12. Comparison of CO₂ Total emissions for variant A, B and C per 1 MW.

values of Variant C are often above the values of Variant A or B. The reason for the high greenhouse gas output is the exclusive use of welded steel. The production of a ton of steel causes approximately 13 times higher CO₂ value compared to the production of concrete.

Since Variant C is not assembled from prefabricated parts but must be welded together from steel, a higher welding effort is required than for the other two variants. In addition, the use of crane and transport systems at the shipyard is increased, which leads to increased CO₂ emissions.

5. Discussion of the results

5.1. LCOE

The calculation considers 21 parameters whereby 6 parameters have a significant impact on the LCOE for the chosen TLP example. For the 6 main parameters, the TLP investment costs (X_6), operating costs (X_9), revenue proceeds (X_{13}), full load hours ($X_{14, b}$) as well as WACC (X_{15}) and generator power rate (X_{17}) are identified. In Fig. 13 the percentage of potential LCOE reduction is shown in the respective interface areas in relation to the current consumption comparative base value (9.52 €/ct/kWh). This graphic illustrates quite clearly that potential savings of 14.7% are possible in the areas of construction and manufacturing of the load-bearing components and the anchoring technology. In the fields of installation and grid connection, savings of up to 11% can also be achieved. However, the greatest potential savings of around 50% can be seen during the operation of the wind turbine and for O&M activities. A favorable WACC as well as the increase in full load hours and generator output have a significant effect.

Fig. 14 presents the LCOE forecast projected for the year 2029 for the three dominant floating substructure concepts. Additionally, the LCOE for the chosen TLP example is illustrated in blue in based on the results of the global sensitivity analysis. It can be shown that the chosen TLP represents an economically viable alternative to other solutions offered in the market. Furthermore, for the other solutions, the LCOE are in the same range.

With regard to the Semi-Submersible, the Gicon[®]-TLP has an about 23.8% cost advantage. Compared to the SparBuoy-concept, the Gicon[®]-TLP can reduce the LCOE by up to 11.6%. Compared

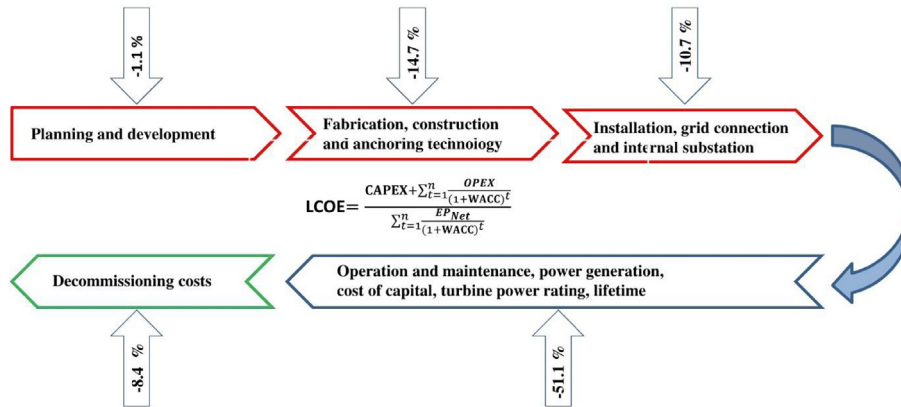


Fig. 13. Quantitative savings in LCOE in the project phases of an offshore wind farm.

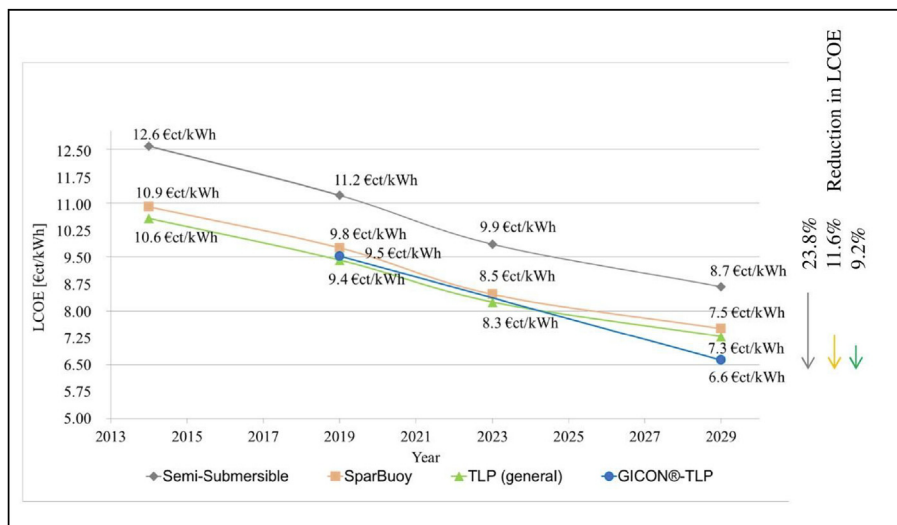


Fig. 14. Forecasted LCOE for floating substructures (based on Nilsson and Westin [24]).

to other TLPs, the Gicon®-TLP offers a cost saving potential of about 9.2%.

It can be concluded that the outlined cost savings potential can also be applied to other foundation concepts e.g. by choosing the same kind of modular concrete elements. Significant reductions are possible for manufacturing costs as well as for O&M. As a result of serial production, the investment costs for all floating foundation concepts can be further reduced. A suitable maintenance concept is essential for the economical operation of an offshore wind farm.

Finally, high full load hours, steady wind speeds and the use of a large generator power rate by using offshore wind farms far from the coast can easily establish power generation forecasts. This can be a major contribution to the grid stabilization.

5.2. CED analysis and CO₂ emissions

The CED and CO₂ emission analysis neglected the recycling aspects. This is one main improvement to be included in ongoing studies. The resulting CED as well as the calculated CO₂ emissions for the TLP are in line with the results of the LCOE analysis and show a reduction for the chosen TLP example. The choice of materials has a decisive effect. Compared to variant C, the substitution of the steel components with the cast nodes and the reinforced concrete pipes leads to significant savings. Other energy-intensive

processes, including the use of shipyard facilities as well as transport and installation at sea, also have an influence on the reduction of CED and CO₂ emissions because reductions are also possible for these energy-related costs and CO₂ emissions through manufacturing process optimization and the reduction of transport distances. A comparison of the chosen TLP with other floating substructures is not possible as at this point in time no comparable LCOE studies have been published.

6. Conclusion and outlook

The paper presents a LCOE study as well as a CED and CO₂ Emissions analysis for the chosen TLP example. It was shown that a significant LCOE reduction is possible by considering a specific realistic range of parameters. 6.63 €/kWh LCOE can be achieved in the best case scenario. Compared to the state of the art for the LCOE, the values obtained are in the expected range for floating wind or lower. This fact is derived from the additional details and validated CPAEX values of this study. As an improved study for future work, the parameter study will be extended to include further examples, including semi-submersibles and floating spar buoy solutions, to see which parameters from the 21 parameters as selected for this study have the most significant impact on LCOE in general or for each individual solution, respectively. In line with the

obtained low LCOE, the CED analysis and the CO₂ emission study present a clear picture with significant advantages of a pre-fabricated steel/pre-stressed concrete element solution compared to welded steel solutions. This result could also be applicable for semi-submersible or spar buoy solutions but the exact results have to be substantiated first as no data on other floating substructures has been published at this point in time. This would be a valuable future topic for evaluation, e.g. a CED analysis and CO₂ emission study for semi-submersible and spar buoy solutions.

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