Journal of Physics: Conference Series

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To cite this article: Kutay Yilmazlar *et al* 2022 *J. Phys.: Conf. Ser.* **2265** 042042

Development of engineering cost models for integrated design optimization of onshore and offshore wind farms

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Abstract. The goal of any multidisciplinary design optimization problem for wind power plants is to reduce the overall levelized cost of the energy. When it comes to designing a wind farm, one has to find the best combination of multiple parameters, such as turbine types, turbine dimensions and farm layout, to ensure the minimum cost. Clearly, since any design parameter may affect several cost items and performance indices of a farm, the most cost-effective solution should handle the mutual coupling among all design variables. For example, increasing the turbine spacing surely has a positive impact on energy production due to the minimization of wake losses, but, at the same time, may have a detrimental impact on the cost of cabling. In order to assist multidisciplinary design activities for wind farms and wind turbines, the present work is aimed at developing a tool for preliminary estimation of the levelized cost of energy of land- and sea-based wind farms. Such a tool is based on a modular architecture, which will ease the integration of the tool in a multi-level design framework. Each module of the tool implements one or more engineering models to estimate all cost items along with the annual energy production of the farm, starting from a few pieces of information related to turbine types and dimensions, farm geometry and wind conditions.

1. Introduction

The focus of wind energy system optimization is moving progressively from single machine to wind farm level. For example, it has been shown that a synergistic control of all turbines belonging to a farm potentially yields the maximum power output with respect to a greedy control where each turbine optimizes its own production [1]. The same approach, i.e. focusing on the whole farm rather than on single machines, also applies to other aspects, such as turbine design, installation, operation and maintenance (O&M) and decommissioning. Each of these aspects contributes together to the levelized cost of energy (LCOE), which is the most important merit figure of the design of a new wind power plant.

Clearly, at the wind farm level, a system design optimization process aimed at minimizing LCOE, not only requires simple but accurate cost models but also the capability to capture all mutual interaction among design variables and performance indices.

As wind farms are increasingly deployed in offshore sites, the importance of design optimization becomes even more evident. In fact, onshore wind farm geometries mostly depend on terrain orography, whereas offshore environment offers a more flexible room for layout optimization. This is particularly beneficial for driving down the cost of offshore operations, e.g., installation and O&M, which make up a higher portion of the total farm cost compared to the onshore case.

In the past years, there has been an effort to develop wind farm cost models for offshore wind farms, with growing attention on floating applications. Some studies have focused on the global potential of offshore wind energy in specific regions [2, 3] and concept analysis of floating wind in terms of life-cycle costs [4–6]. Moreover, examples of cost models implemented for a specific site and turbine design [7, 8] are reported in literature. On top of that, various substructure designs are compared given for different installation sites [9–11]. These works provide valuable cost modelling methods and point out the most significant cost elements to be tackled to drive down the costs of floating wind energy effectively. However, there is a lack of detail within wind farm calculations, which would have a not negligible effect on estimated annual energy production (AEP).

To assist the integrated design of wind turbines and farms, aimed at minimizing the overall LCOE, a tool for estimating the wind farm cost is developed. The present work aims to combine scalable cost functions available in literature with engineering models for wind farm calculations, which are able to capture wind turbine interactions sufficiently accurate without requiring high computation time. By this means, the developed tool can be adapted to any deployment site and selected turbine design, enabling preliminary micro-siting and layout optimization at an early phase of project development. On the other hand, it will allow the integration of the wind farm cost model into turbine comprehensive design tools [12, 13], enabling farm level design optimization studies.

The software developed in this work is called `CosMo-WF` (Cost Model for Wind Farms). The tool uses the open-source code FLORIS [14] to estimate the annual energy production of the farm given the wind statistics, the farm layout and the turbine characteristics. All cost items contributing to LCOE, i.e. the capital expenditure, the operation and maintenance cost and the decommissioning cost, are estimated through heuristic and statistical models, which are collected from the available literature [15–18], and tuned according to available data.

Fully implemented in MATLAB and organized in different modules, the tool can be easily integrated into a multi-level design framework for the optimization of wind turbines and farms.

This paper is organized according to the following plan. Section 2 describes the wind farm cost model, through the definition of all modules and sub-modules. Section 3 reports some analyses performed, showing the main features of the tool. In particular, some sensitivity analyses are performed on various wind farm design parameters such as power density, water depth and distance to shore. Such analyses show a clear presence of an optimal power density for onshore, offshore, and floating farms, associated to a minimum LCOE. Finally, Sec. 4 summarizes the main findings of this work.

2. Description of the wind farm cost model for design optimization

The cost model consists of independent modules, where in each module a different set of cost elements is modelled. The structure of the developed wind farm model is given in Figure 1. To calculate the annual energy production (AEP) of the wind farm, wind farm simulations are performed in the MATLAB version of FLORIS [14].

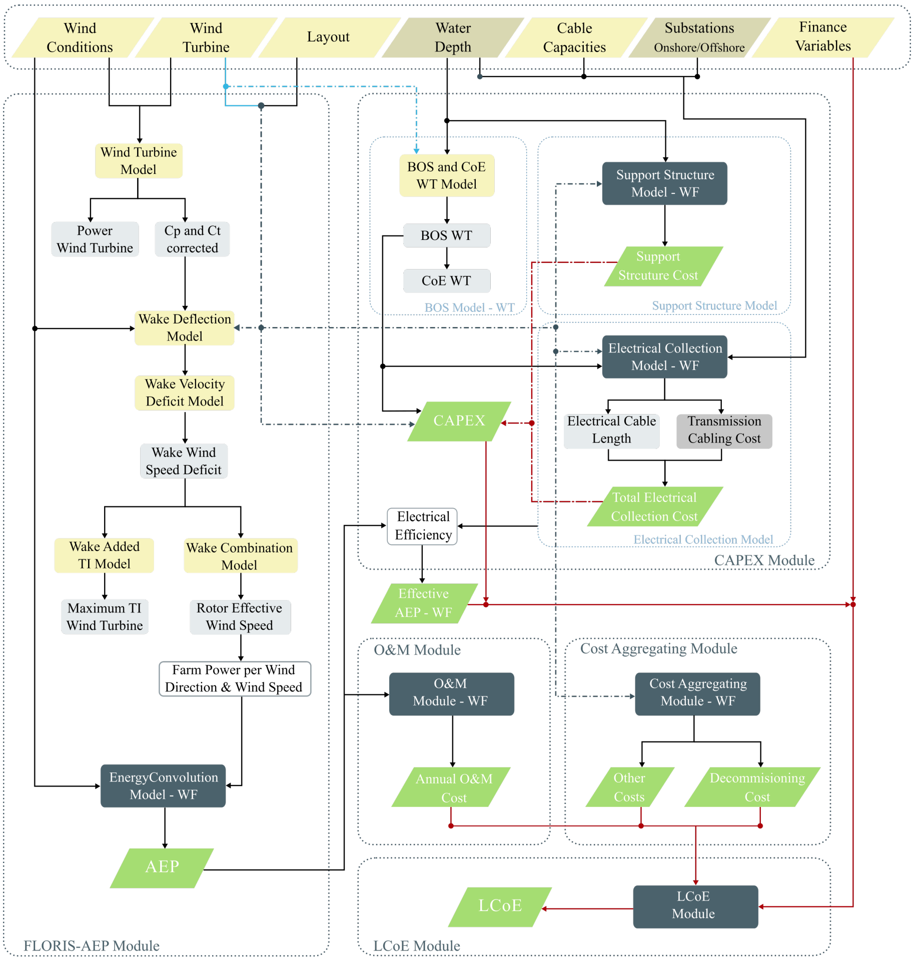

Figure 1. Wind farm cost model architecture

In the next sections, the different modules belonging to the cost model are described.

2.1. FLORIS-AEP module

In this module, the annual energy production (AEP) of a wind farm is computed, taking into account the farm layout and the main wind statistics, i.e. Weibull distribution and wind rose. For a specific averaged inflow condition, defined through a specific wind speed, wind direction and turbulence intensity level, the engineering wake model Floris [14] is used to compute the averaged flow within the farm and the power harvested by each turbine. The analysis is repeated multiple times for different wind speeds and directions, and the obtained results, in terms of farm power, are weighted according to the wind Weibull and rose, so as to yield the expected AEP of the farm, noted as AEP_{WF}.

2.2. CAPEX module

The purpose of this module is to compute the capital expenditure (CAPEX) of the farm.

CAPEX combines together the cost of the single wind turbine balance of station (BOS), the cost for the support structure and the electrical costs. The CAPEX module is divided into four sub-modules, which perform respectively the computation of wind turbine BOS, the computation of support structure costs, the computation of electrical costs, and, finally, the computation of wind farm CAPEX.

The CAPEX of the farm is defined as

$$\text{CAPEX}_{\text{farm}} = N_t \left(\text{TCC} + \text{BOS}_{\text{WT}}\right) + c_{\text{elect}}, \tag{1}$$

where N_t is the number of wind turbines in the farm, BOS_{WT} is the balance of station of the single turbine, and c_{elect} is the cost for the electrical collections. TCC is the turbine capital cost, which is either known, if commercial turbines are used, or is to be computed as a result of a turbine design process [13, 19].

Single wind turbine BOS can be estimated according to [7, 15, 17, 18] as function of foundation types and characteristics and of turbine overall features (e.g. rated power, diameter and hub height), as detailed in paragraphs 2.2.1, 2.2.2 and 2.2.3. The estimation of the electrical collection cost for the whole farm, on the other hand, is detailed in 2.2.4.

2.2.1. BOS for onshore turbines.

In the case of onshore turbines, BOS comprises the cost of turbine foundation c_{found}, transportation c_{transp}, installation c_{instal}, civil work c_{civil}, electrical interface $c_{\text{elec.interf}}$ and engineering c_{eng}, as

$$\text{BOS}_{\text{WT}} = c_{\text{found}} + c_{\text{transp}} + c_{\text{instal}} + c_{\text{civil}} + c_{\text{eng}}. \tag{2}$$

For onshore farms, equations (3), taken from [15], are employed to estimate the cost belonging to BOS expressed in k$ of 2002,

$$\begin{aligned}
c_{\text{found}} &= \left(303.24\, h_{\text{hub}}\, R^2 \pi\right)^{0.4037} /1000, &(3a)\\
c_{\text{transp}} &= \left(1.581\text{E}{-5}\, {P_{\text{ratedkW}}}^2 - 0.0375\, P_{\text{ratedkW}} + 54.7\right)\, P_{\text{ratedkW}}/1000, &(3b)\\
c_{\text{instal}} &= 1.965\, (h_{\text{hub}}\, 2R)^{1.1736} /1000, &(3c)\\
c_{\text{civil}} &= \left(2.17\text{E}{-6}\, {P_{\text{ratedkW}}}^2 - 0.0145\, P_{\text{ratedkW}} + 69.54\right)\, P_{\text{ratedkW}}/1000, &(3d)\\
c_{\text{eng}} &= (9.94\text{E}{-4}\, P_{\text{ratedkW}} + 20.31)\, P_{\text{ratedkW}}/1000, &(3e)
\end{aligned}$$

where h_{hub} is the turbine hub height, R is the turbine rotor radius and P_{ratedkW} is the turbine rated power expressed in kW.

Before computing the total BOS cost with (2), all contributions in (3) have to be scaled up to present currency as described in [15].

2.2.2. BOS for offshore turbines.

For offshore turbines, also the cost of port and equipment c_{port} and the scour protection c_{scour} should be considered. The final estimate equation for offshore BOS is

$$\text{BOS}_{\text{WT}} = c_{\text{found}} + c_{\text{transp}} + c_{\text{instal}} + c_{\text{civil}} + c_{\text{eng}} + c_{\text{port}} + c_{\text{scour}}. \tag{4}$$

The two additional entries, c_{port} and c_{scour}, can be estimated following [15], as

$$\begin{aligned}
c_{\text{port}} &= 0.020 P_{\text{ratedkW}}, &(5a)\\
c_{\text{scour}} &= 0.055 P_{\text{ratedkW}}. &(5b)
\end{aligned}$$

Moreover, some of the contributions in (4) should be adapted for the offshore scenario. In particular, the foundation cost in 2014 k\$ can be taken from [17] as

$$c_{\text{found}} = 0.345\,\mathrm{e}^{(0.182 D_{\text{water}})} P_{\text{rated kW}}. \tag{6}$$

Again for offshore turbines, a suitable estimate of the cost of the installation in 2010 k\$ can be found in [18] as

$$c_{\text{instal}} = 3.4\,(h_{\text{hub}} + 50)\,. \tag{7}$$

Finally, cost of engineering and civil works in 2003 k\$ can be estimated as

$$c_{\text{eng}} = 0.037 P_{\text{rated kW}}, \tag{8a}$$
$$c_{\text{civil}} = 60. \tag{8b}$$

2.2.3. BOS for floating turbines.

The estimates for BOS in the floating offshore case is based on the treatment of Sec. 2.2.2, with a modification in the foundation and installation costs, and the addition of the mooring lines and anchors cost c_{moor}.

In particular, as reported in [7], c_{found}, c_{moor} and c_{instal} in 2015 k€ are

$$c_{\text{found}} = 1.252\,(1.1273 - 2.83\text{E}{-5}\,P_{\text{rated kW}})\,P_{\text{rated kW}}, \tag{9a}$$
$$c_{\text{moor}} = (0.104 + 1.742\text{E}{-3}\,D_{\text{water}})\,P_{\text{rated kW}}, \tag{9b}$$
$$c_{\text{instal}} = 0.275\,(1.3325 - 6.62\text{E}{-5}\,P_{\text{rated kW}})\,(3122.5\,P_{\text{rated kW}}{}^{-0.946})P_{\text{rated kW}}. \tag{9c}$$

For c_{instal}, the first term in parentheses denotes the scaling with regard to turbine installation, whereas the second term scales the cost parameter respecting substructure installation.

2.2.4. Electrical collection sub-module.

The cost of the electrical collection c_{elect} for the whole wind farm consists of grid cabling and transmission to the substation. For offshore farms, also the cost of cabling between the offshore station and the shore system is to be included. Accordingly, one may define the c_{elect} as

$$c_{\text{elect}} = c_{\text{elect install}} + c_{\text{elect cabling}} \tag{10}$$

for onshore farms, and

$$c_{\text{elect}} = c_{\text{elect install}} + c_{\text{elect cabling}} + c_{\text{elect transmiss}} \tag{11}$$

for offshore farms, where $c_{\text{elect install}}$, $c_{\text{elect cabling}}$ and $c_{\text{elect transmiss}}$ are respectively the cost of electrical installation, cabling and transmission between offshore and shore electrical stations.

At first the electrical interface cost for the single turbine in an onshore farm is estimated following [15], as

$$c_{\text{elec.interf}} = \left(3.49\text{E}{-6}\,P_{\text{rated kW}}{}^2 - 0.0221\,P_{\text{rated kW}} + 109.7\right)\,P_{\text{rated kW}}/1000. \tag{12}$$

Then, the wind farm electrical installation cost is assumed to be the 65% of $c_{\text{elec.interf}}$ multiplied for the number of turbine, as

$$c_{\text{elect install}} = 0.65\,c_{\text{elec.interf}}\,N_t. \tag{13}$$

For the offshore case, Ref. [15] suggests the following estimation of the electrical interface cost, in 2003 k$,

$$c_{\text{elec.interf}} = 0.26 P_{\text{rated kW}}. \tag{14}$$

The same structure of (13) is maintained for the offshore case. However, a dedicated study was performed to estimate which percentage of $c_{\text{elec.interf}}$ is to be used. The model suggested in [15] was then tuned using the data reported in Ref. [7, 17, 18], finding a percentage equal to 47%. Accordingly, for offshore farms, the cost of electrical installations is estimated as

$$c_{\text{elect install}} = 0.47\, c_{\text{elec.interf}}\, N_t. \tag{15}$$

The cost of cabling within the farm $c_{\text{elect cabling}}$, i.e. excluding the connection from the offshore to the shore station, is to be determined according to the length of the cables. To this end, only one substation in the farm and, as suggested in Ref. [20], a radial configuration of cabling are considered. Figure 2 provides for a schematic view of the electrical cabling configuration. According to the farm layout, the total cable length l_{cabling} is computed and $c_{\text{elect cabling}}$ is estimated as

$$c_{\text{elect cabling}} = l_{\text{cabling}}\, c_{\text{cable}}, \tag{16}$$

where c_{cable} is the cost of the cables per unit length, [18].

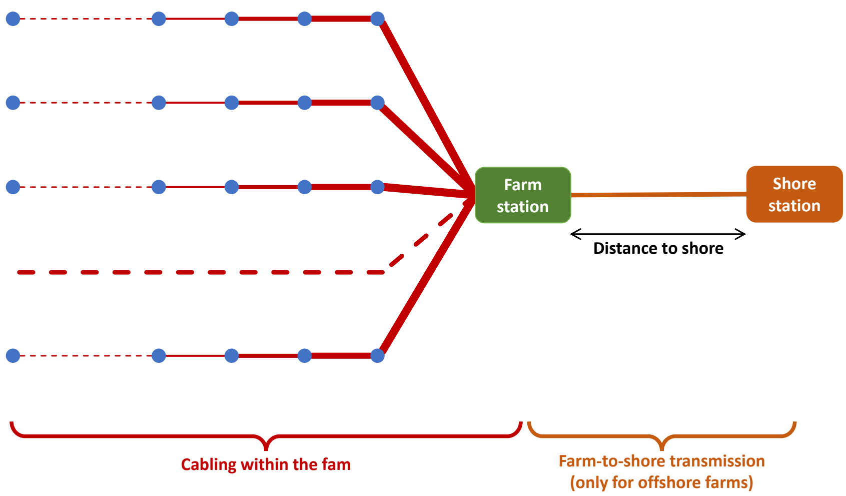

Figure 2. Cabling configurations. Blue dots: turbines; Red lines: array cables within the farm; Orange line: export cable for transmission between farm station and shore (only for offshore farms).

Only for offshore farms, following [7], $c_{\text{elect transmiss}}$ is finally estimated in 2015 k$, as

$$c_{\text{elect transmiss}} = 0.094\,(0.0116\, d_{\text{shore}} + 0.5363)\, N_t P_{\text{rated kW}}, \tag{17}$$

where d_{shore} is the distance between offshore and shore stations in km.

2.3. Wind farm annual operating expenses

The estimation of wind farm annual operating expenses AOE_{WF} is computed as

$$\text{AOE}_{\text{WF}} = \frac{\text{LEASE}_{\text{WF}} + \frac{1}{\eta_{elec}}\left(\text{DECOM}_{\text{WF}} + \text{OM}_{WF}\right)}{\text{AEP}_{\text{WF}}}, \tag{18}$$

where η_{elec} is the electrical efficiency of the farm, while wind farm operation and maintenance cost OM_{WF}, decommissioning cost $\mathrm{DECOM_{WF}}$ and land (or sea) lease, $\mathrm{LEASE_{WF}}$, are estimated as in paragraph 2.3.1 and 2.3.2.

2.3.1. Operation and maintenance module.
Annual wind farm operation and maintenance cost OM_{WF} in 2002 k\$ can be estimated, following treatment reported in [15], as function of wind farm annual energy production in MWh, as

$$\mathrm{OM}_{WF} = 0.007\mathrm{AEP_{WF}}, \tag{19}$$

for onshore farms, and

$$\mathrm{OM}_{WF} = 0.02\mathrm{AEP_{WF}}, \tag{20}$$

for fixed-bottom offshore farms. For floating wind farms, an additional platform O&M cost term in 2015 k€ according to [7] is considered on top of fixed-bottom $\mathrm{OM_{WF}}$. The final equation is formulated as:

$$\mathrm{OM}_{WF} = 0.02\mathrm{AEP_{WF}}\,2002\mathrm{k\$} + 0.024(1.2778 - 5.95\mathrm{E}{-5}P_{\mathrm{ratedkW}})P_{\mathrm{ratedkW}}N_t\,2015\mathrm{k€}. \tag{21}$$

2.3.2. Wind farm decommissioning module and land-sea lease cost.
In Ref. [15] an estimate of the decommissioning cost $\mathrm{DECOM_{WF}}$, in 2002 k\$, for onshore farms is given as

$$\mathrm{DECOM_{WF}} = 0.0107\,P_{\mathrm{ratedkW}}N_t. \tag{22}$$

For fixed-bottom offshore farms, following the treatment in [18], $\mathrm{DECOM_{WF}}$ is estimated, in 2010 k\$, as a function of the cost of the installation of all turbines, as

$$\mathrm{DECOM_{WF}} = 0.91c_{\mathrm{instal}}N_t, \tag{23}$$

where c_{instal} is the installation cost of a single turbine as computed in 7. For floating wind farms, decommissioning costs are estimated as follows [7]:

$$\mathrm{DECOM_{WF}} = 0.168(0.905 + 0.0194\,d_{\mathrm{shore}})P_{\mathrm{ratedkW}}N_t, \tag{24}$$

Finally, the cost for land (or sea) lease for the whole farm, $\mathrm{LEASE_{WF}}$, is simply computed as

$$\mathrm{LEASE_{WF}} = 0.00108\mathrm{AEP_{WF}}. \tag{25}$$

2.4. LCOE module
The levelized cost of the energy model (LCOE) of the whole farm is adapted from [15], which was defined for the single turbine. Specifically, the farm LCOE, $\mathrm{LCOE_{WF}}$ can be defined as

$$\mathrm{LCOE_{WF}} = \frac{\mathrm{FCR}\cdot\mathrm{CAPEX_{WF}}}{\mathrm{AEP_{WF}}} + \mathrm{AOE_{WF}}, \tag{26}$$

where FCR is the *fixed charge rate*, $\mathrm{CAPEX_{WF}}$ is the capital expenditure of the wind farm, $\mathrm{AOE_{WF}}$ is the annual operating expenses of the wind farm, whereas $\mathrm{AEP_{WF}}$ is the annual energy production of the farm, estimated through Floris model as reported in 2.1.

3. Results

In this section, the presented wind farm cost model is tested through sensitivity analyses on various parameters. To begin with, the effect of wind farm power density is examined. A wind farm layout, comprised of 12 5-MW turbines based on Alpha Ventus wind farm [16], is adopted. Turbines are positioned in 4 rows × 3 columns, separated by 7D and 6.5D, in easting and northing directions, respectively. For the offshore wind farm cases, the site is characterized by a water depth D_w of 35 m and a distance to shore d_s of 45 km. While maintaining the row and column orientation, grid spacing is proportionally perturbed to vary power density, denoted as the rated power of the wind farm per installed area. The results for onshore and offshore cases are presented in Figure 3. LCOE values are normalized by the maximum value for each configuration. It appears from the AEP curve that, as the density decreases, the AEP increases due to the lower wake losses, resulting from a greater turbine spacing. However, due to the increase mainly in the electrical collection costs, LCOE increases at low densities, leading to a minimum LCOE at about 7MW/km^2 in both onshore (purple line) and offshore (red line) cases. It is observed that the floating wind farm (red dotted line) is more sensitive to AEP reduction, compared to monopile configuration. Although the electrical collection cost is estimated with identical models for both offshore cases, the overall share of electrical collection costs is less for floating configuration. This makes the electrical costs counteract the AEP decrease less efficiently, which also explains the minimum LCOE shifted to about 6MW/km^2.

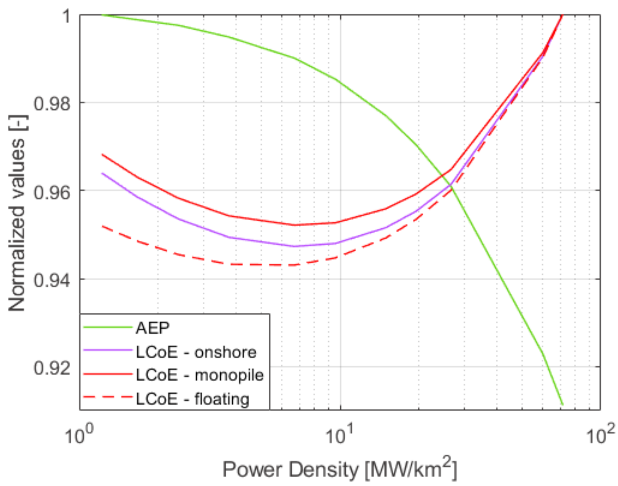

Figure 3. Sensitivity analysis on wind farm power density

As a further analysis, a sensitivity study on site characteristics is performed for two offshore cases, one with monopile substructure and another with floating platform. The floater type is not specified in the model, therefore the obtained results represent a preliminary cost estimation of a generic floating platform. Figure 4 depicts the change in various cost elements normalized by the baseline site configuration, where $D_w = 35$m and $d_s = 45$km. As expected, the support structure costs for monopile configuration is highly dependent on water depth. On the other hand, the floating configuration features a lower dependence, which is mainly due to mooring lines and anchor costs. The electrical costs remain relatively constant, and mainly independent of the configurations, as discussed before. Finally, both LCOE curves reveals that floating configuration is fairly insensitive to the water depth compared to the monopile case.

In order to make a more relevant analysis, the cost elements are analyzed in terms of a combination of D_w and d_s. To this purpose, a realistic bathymetric profile is adopted from

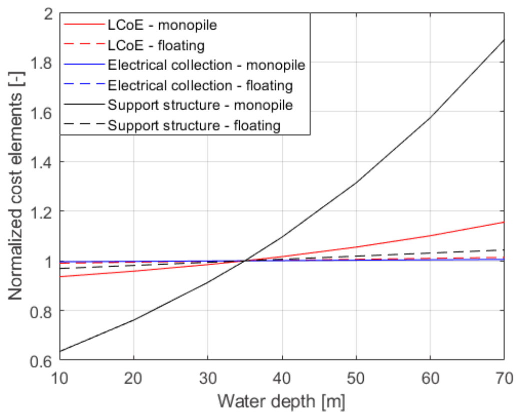

Figure 4. Sensitivity analysis on D_w

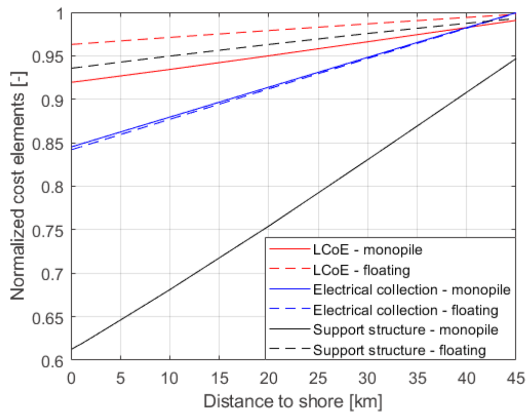

Figure 5. Sensitivity analysis on D_w and d_s

shore to the offshore substation point of the offshore baseline case. Moreover, for the floating case, the slope of water depth is doubled to reproduce an offshore site more suitable for floating wind turbine deployment. Within this analysis, the baseline floating site is located at D_w of 70 m instead of 35 m. The estimated reference values can be extracted from Table 1.

Table 1. Reference values from offshore baseline cases

Substructure	d_s [km]	D_w [m]	LCOE [€/MWh]	$C_{electr.}$ [M€]	$C_{supp.}$ [M€]
Monopile	45	35	97.63	1.743	3.606
Floating	45	70	137.58	1.753	9.189

The normalized cost elements are given in Figure 5 as a function of d_s, which also defines D_w at given position. As opposed to sole D_w analysis, it is indicated that electrical collection costs highly depend on site characteristics, especially on d_s due to the costs arising from power transmission to the onshore substation. Again, LCOE and support structure costs of floating wind turbines are less sensitive to the site characteristics, which is in line with the LCOE studies of floating offshore wind in the literature [4]. It is important to note that the LCOE curves in Figure 4 and 5 have an increasing trend as the installation site is moved further away from shore. This is not necessarily true due to the fact that the wind resource at far offshore sites is usually characterized by higher wind speeds and less turbulence, which positively impacts the AEP. In this study, the wind resource information, including the wind speed and direction distribution, are considered identical regardless of the chosen site, in order to simplify the problem and focus more on the development of the wind farm cost model.

4. Conclusions

The presented work proposes a new wind farm cost model to be implemented in wind farm and turbine optimization studies. Due to its modular nature, it shows a potential to integrate wind turbine design into a wind farm design perspective, both in onshore and offshore environments. The wind farm cost elements are modeled with values from different sources in the literature, taking into account the types, dimensions of the turbine and site characteristics. A special consideration is given to the offshore cost modelling, for which a wide range of cost uncertainties exists, especially for floating wind farms. The developed cost model is then employed for both land-based and offshore configurations to run sensitivity analysis of LCOE on power density, water depth and distance to shore, where the latter two parameters are studied only for offshore wind farms with monopile and floating substructures. The results have demonstrated the capability of the tool to generate reasonable preliminary cost estimations to find optimal wind farm parameters in an early design stage. The first results presented here reveal that, the electrical infrastructure costs play a significant role in wind farm design. Moreover, compared to its counterparts, floating wind farms show a greater potential for a relative LCOE reduction by performing layout optimization.

Ongoing work is to integrate this cost model into a holistic system design optimization tool, to be used to simultaneously design site specific wind turbines and wind farm layouts. The cost models will be further enhanced and updated according to the present technology and market developments, with a specific focus on floating wind energy. Hereto, an important aspect to be ameliorated is the modelling of cost elements with regard to the different types of floater platforms. Beside the material and construction costs of floating substructures, this would also define installation, decommissioning and O&M strategies.

Acknowledgement
This work has been partially conducted within the FLOAWER project. This project has received funding from the European Union's Horizon H2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement N°860579.

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