How do technological choices affect the economic and environmental performance of offshore wind farms?

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Abstract. The ongoing energy transition towards fully sustainable energy systems requires designing wind farms looking beyond the sole levelized cost of energy, in order to concurrently ensure not only the economic profitability but also the environmental friendliness of future plants. Within this new approach to design, it becomes necessary to understand the effects that various possible technological choices have on both the economic and the environmental performance of a wind farm. This study presents a framework designed to support these coupled economic-environmental assessments. The capabilities of the code are showcased by analysing the impact of different choices in terms of support structure type, specific power, tower height, powertrain type, and array and export voltage level for an exemplary offshore farm, chosen here as the IEA Wind 740-10-MW Reference Offshore Wind Plant with irregular layout. While the effects of many technological choices on the cost of energy are surely already well understood by industry, the present analysis shows that — at least in this specific case — climate change impacts are mainly driven by steel production, due to the massive amount of required material, but also, interestingly, by vessel activities. A low specific power, tall towers, and a high export cable voltage appear to offer the greatest potential for the concurrent improvement of the coupled environmental and economic performance of the plant.

1. Introduction

Over the last decades, the development of wind energy technology has primarily targeted the reduction of the Levelized Cost Of Energy (LCOE), to ensure competitiveness on the electricity markets. With the sector reaching cost parity and facing ambitious growth targets, metrics beyond LCOE need to be considered in wind energy system design, such that the environmental and economic sustainability of the generated electricity can be guaranteed.

The impact of technological choices (for example, offshore support structures or powertrain type) on LCOE is well understood. Looking beyond LCOE, an increasing number of studies is now focusing on wind energy system optimization for economic value [1, 2]. On the environmental side, various life cycle assessment (LCA) analyses have been conducted to quantify the environmental impact of different wind turbine and farm configurations [3–5]. Furthermore, multi-criteria assessments are being proposed, which consider the coupled effects of techno-economics, environmental impacts, and socio-economics [6]. However, most studies looking beyond economics have so far been limited to a post-design assessment, and do not include turbine or farm design capabilities for cost and value optimization. In fact, only a few studies have proposed parameterized LCA models that can support turbine [7–9] and farm [10] design.

To the authors' knowledge, only one study has considered the design of wind energy systems for combined economic and environmental performance, and so far limitedly to the onshore case [8].

This work presents some of the functionalities of a new design framework that is being developed at TUM to enable the coupled economic-environmental design of wind energy systems. Specifically, the paper describes the modeling of different technological choices for offshore wind farms. The capabilities of the code are showcased analyzing the irregular-layout IEA Wind 740-10-MW Reference Offshore Wind Plant [11]. The analysis is conducted using as metrics the economic and environmental Cost Of Energy ($COE_{€}$ for LCOE, and COE_{CO2} – also termed carbon footprint – for climate change impact) and Net Value Of Energy ($NVOE_{€}$ for profit, and $NVOE_{CO2}$ for grid-avoided greenhouse gases). The present study is limited to the analysis of the effects of various technological choices on a representative test case, whereas more complete design studies will be presented in future publications. Although not exercising the full capabilities of the code, the present analysis still delivers some interesting insight on the drivers and the opportunities for designing future more sustainable and yet still economically viable offshore farms.

2. Methodology

Figure 1 illustrates the data and model flows that support the forward analysis functionalities of the newly developed **D**esign and **E**valuation **T**oolchain with **E**co-**C**onscious **T**argets (DETECT). The complete code implementation is more general and includes the ability to optimize designs according to multiple concurrent objectives, although these capabilities are not used in the present work, and therefore are not discussed further. The approach is similar to the one used in ref. [8], but adapted for offshore turbines and extended to the plant level. The analysis covers all wind farm components up to and including the onshore substation. Details about the definition of economic and environment cost, value, and net value of energy can be found in [8].

2.1. Plant setup and sizing

In this work, DETECT is used to represent an existing wind farm, and to evaluate the effects of various technological choices on its economic and environmental characteristics. This requires first setting the turbine, farm, and site properties to match the characteristics of the considered plant. Next, the remaining parameters are sized based on appropriate models for each wind farm component and each one of the considered technological choices.

The *turbine-specific model* sizes all components of the rotor nacelle assembly (RNA) [12]. For monopile-based support structures, monopiles and towers are designed following ref. [13], and the transition piece is sized based on ref. [14]. For jackets, spar-buoys, and semisubmersible

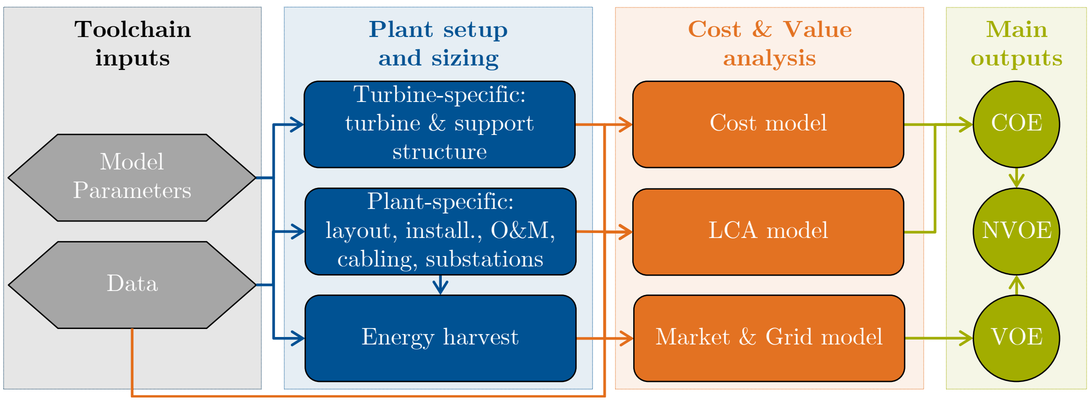

Figure 1. Forward analysis mode of the DETECT code.

floaters, submarine structures and towers are scaled according to refs. [14] and [15], respectively. Scour and corrosion protection are dimensioned following the guidelines of refs. [16] and [17, 18], respectively.

The *plant-specific model* determines electric infrastructure, vessel activities for installation [14], operation & maintenance (O&M) [14, 19, 20] and decommissioning, and end-of-life (EoL) strategies [21]. The on- and offshore substations are sized according to ref. [14]. Array and export cabling are dimensioned using the cabling plan of ref. [11] and an offshore power cable database [22]. Based on the predefined voltage level for array and export system, respectively, the cable type with smallest capacity surplus with respect to the transferred rated power is selected for each cable section. If a single cable is not sufficient, several cables are laid out in parallel. For O&M, a failure rate model [19] is implemented. Following a conservative approach, a vessel for replacement [14] or reparation [20] is called to site each time a failure occurs. Additionally, annual service [20] and lubricant replacement [23] are modelled. Decommissioning is considered as reversed installation, but scour protection material is left on the seafloor.

The *energy harvest model* uses FLORIS [24] to assess the annual energy production (AEP) accounting for wake losses as suggested in ref. [11]. Furthermore, the analysis includes performance losses due to non-ideal operating conditions [25], powertrain losses at different load [12], downtime based on the failure rate model, power cable losses [26] in each cable section for each inflow condition evaluated by FLORIS, and transformer losses [27]. When varying rotor diameter or rated power of a given turbine model, power and thrust coefficients are adapted considering fixed aerodynamic performances (fixed data-triplets of power coefficient, pitch angle, and tip speed ratio) by means of look up tables as defined for the reference turbine.

2.2. Cost & value analysis

The output of the plant setup and sizing tool is then processed in the tool for cost & value analysis to determine COE and NVOE of the studied wind farm. The *economic cost model* assesses turbine costs [12], balance-of-plant costs [14], and project costs [28]. Transportation costs are calculated based on ref. [29] with transport distances as suggested by ref. [21]. End-of-life cash flows consider salvage value for recycled materials [30], value of reselling installed spare parts as suggested by ref. [31], and waste management cost as recommended by ref. [30, 32]. Taxes are neglected. All cash-flows are scaled based on annual inflation rates [33], nominally discounted [34], and converted [35] to 2020-Euros. Finally, $\text{COE}_{€}$ is calculated as a function of total life cycle costs ($TLCC$), AEP, and annuity A:

$$COE_{€} = \frac{TLCC}{AEP \cdot A}.$$

The *Life Cycle Assessment (LCA) model* has been developed following the standardization framework ISO 14040 and ISO 14044. The parameterized and automated model quantifies the global warming potential over 100 years associated to the production of electricity from the wind farm, expressed in $kg\,CO_2eq/MWh$ following the IPCC lifecycle impact assessment guidelines [36]. Only the impact on climate change is evaluated, whereas other environmental impact categories are disregarded for now, although they will be included in future releases of the code. Component masses as calculated in the plant design model are allocated to up to 33 different materials [8, 14, 17, 18, 22, 28, 37–40]. More than 60 reference activities from the ecoinvent database v3.8 [41] are used for approximating the life cycle of all wind farm components from cradle to grave. The ecoinvent system model 'Allocation cut-off by classification' is chosen. To capture the benefits and burdens of recycling and recycability, the circular footprint formula [42] has been implemented. To determine the allocated burden for upstream impact of recycled material input, the necessary activities for the extraction of the respective virgin material are taken from the ecoinvent database. Similarly, materials that are recycled at the end of life provide a certain credit, which corresponds to the burden due to the extraction of the virgin material that is allocated to the next user of that same material. The allocation is determined by means of burden and credit factors between supplier and user of each recycled material, as provided by ref. [42]. Material extraction and manufacturing are based on European datasets [41]. Transport distances of components from manufacturing to port are taken from ref. [21]. The impact of vessel activities is calculated through the fuel consumption [43] for all transport, installation, maintenance and decommissioning activities, and the vessel lifecycle impact is modelled with the relevant ecoinvent datasets. Spare parts for component replacement are modeled from cradle to grave. For resold components, 80% of the emissions are transferred to the buyer. Recycling rates are taken from ref. [21]. Waste components are either incinerated or landfilled with the ratios suggested by refs. [21] and [41]. Finally, COE_{CO2} is calculated as a function of the total life cycle emissions ($TLCE$), AEP, and design lifetime Y:

$$COE_{CO2} = \frac{TLCE}{AEP \cdot Y}.$$

The *market & grid model* estimates the Value Of Energy ($\text{VOE}_{€}$ for market value, and VOE_{CO2} for displaced-from-grid greenhouse gases) based on linear regressions between historic time series of day-ahead market prices and average grid greenhouse gas emissions with the site-specific wind rose. The time series for market prices and energy mix of the Dutch electricity market zone are taken from ref. [44], while the time series for inflow conditions are based on ref. [45]. The energy mix is further translated into grid greenhouse gases by means of ecoinvent datasets for Dutch electricity generation from the respective energy sources. The regression model takes into account data from the years 2015–2018, and data is normalized by the annual mean values. It is assumed that all the produced energy is sold in the Dutch day-ahead market. VOE is calculated by integrating the product of the plant power rose and the regression curves over wind speed. The annual averages of electricity price and grid greenhouse gases are frozen to the mean value between 11/2021 and 11/2023 [44] over the plant lifetime. Finally, $NVOE$ is calculated as

$$NVOE = VOE - COE.$$

3. Results

The IEA Wind 740-10-MW Reference Offshore Wind Plant with irregular layout [11] is selected as case study. The farm consists of 74 IEA 10-MW reference turbines [46] and its main characteristics are listed in table 1. Turbine and substation coordinates, wind rose, shear exponent, turbulence intensity, bathymetry, and cabling plan are taken from ref. [11]. Coordinates of the export cable route are extracted from ref. [48], representing the existing route from the offshore substation Borssele Alpha to the onshore substation close to the village

Table 1. Main characteristics of the case study, based on [11, 34, 44, 46, 47].

Parameter	Baseline	Parameter	Baseline
Rated power	10 MW	Distance to installation port	80 km
Rotor diameter	119 m	Distance to service port	50 km
Nr. turbines	74	Offshore platform height	10 m
Significant wave height	4.52 m	Coating material	Epoxy
Significant wave period	9.45 s	Sacrificial anode	Aluminium
Lifetime	25 years	Mean grid carbon footprint	523.9 kgCO_2eq/MWh
Nominal discount rate	5.29%	Mean electricity price	179.6 €/MWh

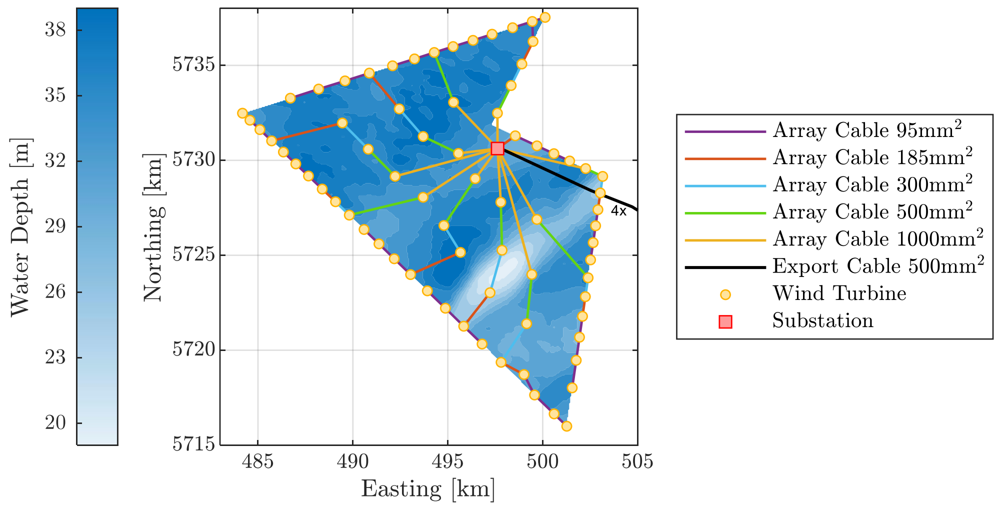

Figure 2. Layout and cable plan of the reference wind farm, assumed as baseline for the technology-impact analysis.

Table 2. Considered technologies with baseline solutions [11] and their alternatives.

Technology	Baseline	Alternatives
Support Structure	Monopile	Jacket, Semisubmersible, Spar
Specific Power	325 W/m²	235-400 W/m²
Hub Height	119 m	105-150 m
Powertrain	Direct-Drive	3S HighSpeed, 2S MediumSpeed
Array Voltage	66 kV	33 kV, 110 kV
Export Voltage	220 kV	150 kV, 275 kV

of Borssele. The toolchain parameters are adapted according to the available data in order to best approximate the wind farm. Figure 2 presents plant layout, bathymetry and cabling plan for the baseline configuration. Table 2 lists the technologies that are considered in this work as alternatives to the choices of the baseline wind farm.

3.1. Baseline

The AEP analysis is presented in figure 3 by means of a sankey diagram. Most losses in energy harvest result from downtime, followed by powertrain, wake, and export cable losses. All losses sum up to about 24% of the gross AEP. The net AEP corresponds to a capacity factor of 45.5%.

Table 3 provides the results for COE, VOE, and NVOE for the baseline configuration. $VOE_{€}$ and $NVOE_{€}$ are relatively high due to the assumed average electricity price, representing spot market prices of the years 2021 to 2023. VOE_{CO2} and $NVOE_{CO2}$ are almost 30 times larger than COE_{CO2}, highlighting the enormous potential of wind energy technology to decrease the climate change impact of grid electricity.

The results for COE_{CO2} are broken down in figure 4. The energy-intensive material extraction and manufacturing processes, especially related to structural steel, are contributing the most. However, a significant credit for material extraction is achieved at the end of life due to recycling. The relative contribution of all vessel activities to COE_{CO2} exceeds 30%. Most of these emissions result from the O&M phase and are linked to repair and replacement activities of nacelle components. In fact, the nacelle contains the most-impactful components, followed by the

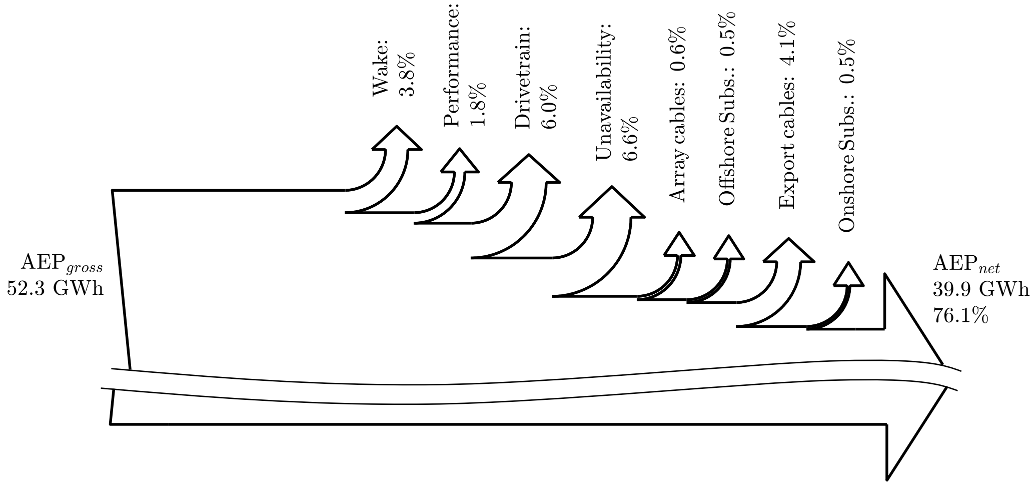

Figure 3. Sankey diagram of the energy production per turbine.

Table 3. Design metrics [8] for the baseline.

	Economic perspective [€ / MWh]		Environmental perspective [kgCO$_2$eq / MWh]	
Cost	COE$_€$	92.5	COE$_{CO2}$	16.8
Value	VOE$_€$	166.1	VOE$_{CO2}$	506.2
Net value	NVOE$_€$	73.6	NVOE$_{CO2}$	489.5

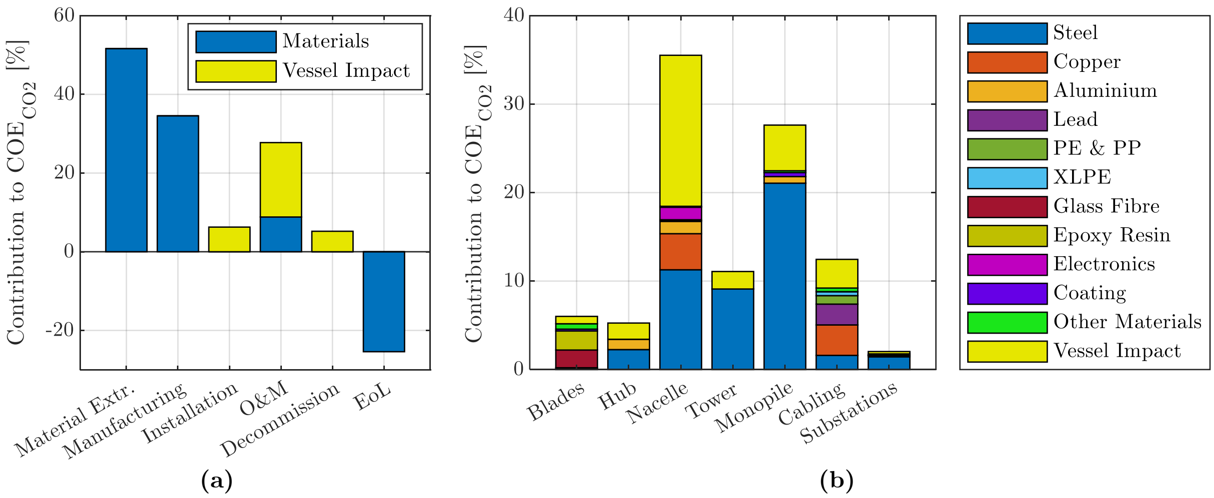

Figure 4. COE$_{CO2}$ breakdown by **(a)** life phases for materials and vessel impact, and **(b)** components, materials, and vessel impact.

monopile due to its massive steel content, in turn followed by cabling and tower.

Figure 5 reports the breakdown of COE$_€$. In general, trends in life phases are similar to figure 4a. Most emissions result from the production of components of the RNA, followed by O&M / OPEX. Other significant contributors to COE$_€$ are installation and global costs. The latter refer to project costs that are not allocatable to components or OPEX. Compared to EoL-credit for COE$_{CO2}$, the salvage value has only a modest contribution to COE$_€$.

3.2. Technological alternatives

The first evaluation of technological alternatives addresses the impact on COE of different support structures, for a parametrically varying average water depth. The results are presented in figure 6. Since neither wind rose nor turbine type are changed, energy harvest is not affected and, therefore, changes in NVOE are proportional to those in COE and not discussed further. For the reference site with a mean water depth of 33.8 m, only fixed-bottom support structures are applicable, and monopiles appear to perform best. With increasing water depth, COE for fixed-bottom support structures grows rapidly, whereas the results for floaters exhibit only a modest dependency. Within the validity ranges of the models, monopiles feature a lower COE than jackets at the reference site. For waters deeper than 40–50 m, semisubmersible floaters appear to outperform fixed-bottom jackets. For the evaluated water depth range, the economic performance of the two studied floaters is similar, whereas semisubmersibles outperform spars with respect to COE_{CO2}.

Next, the impact of specific power on COE and NVOE is evaluated. The rotor diameter is varied, whereas rated power is frozen to the baseline value. The results are shown in figure 7. At the reference site, a larger rotor allows for increased generation at low wind speeds where electricity prices and grid greenhouse gas emissions tend to be higher, resulting in significantly improved economic and environmental performance. A minimum for COE is found around

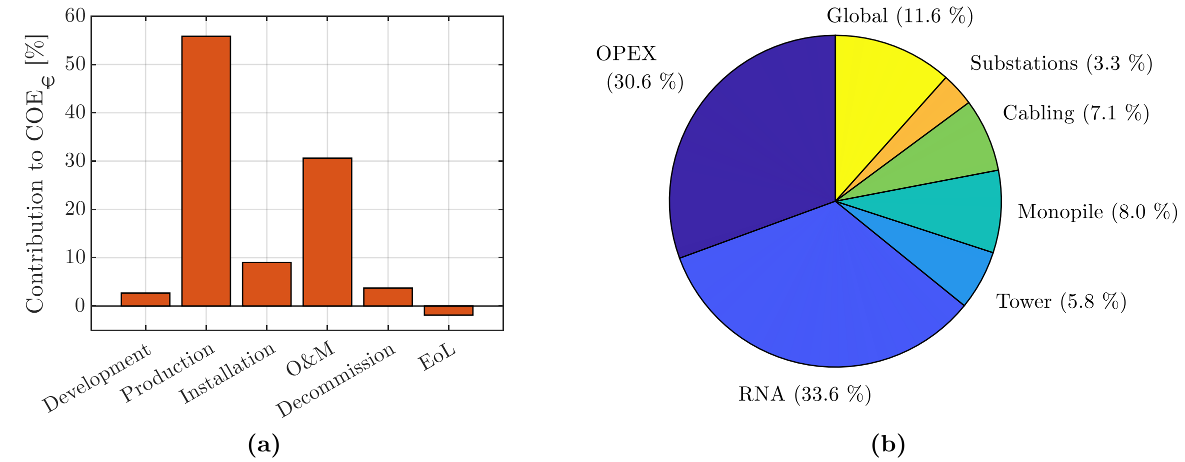

Figure 5. $COE_{€}$ breakdown by **(a)** life phases, and **(b)** components and unallocatable costs (OPEX, and 'Global' representing project and port costs).

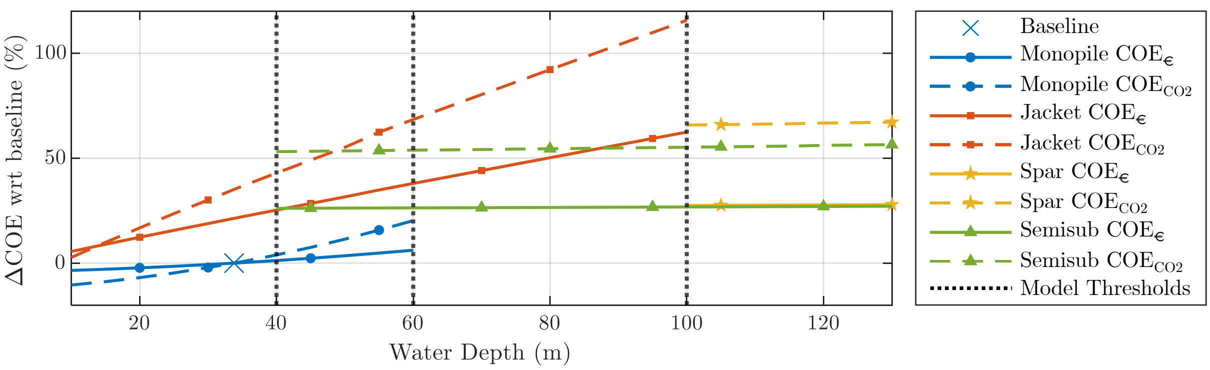

Figure 6. COE analysis with different support structure types for parametrically varying average water depth.

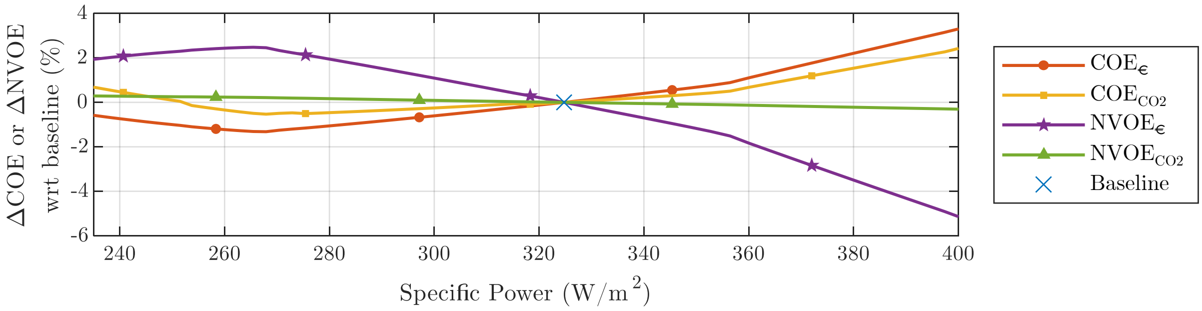

Figure 7. Changes in COE and NVOE with parametrically varying specific power. Rated power is frozen to the baseline value of 10 MW.

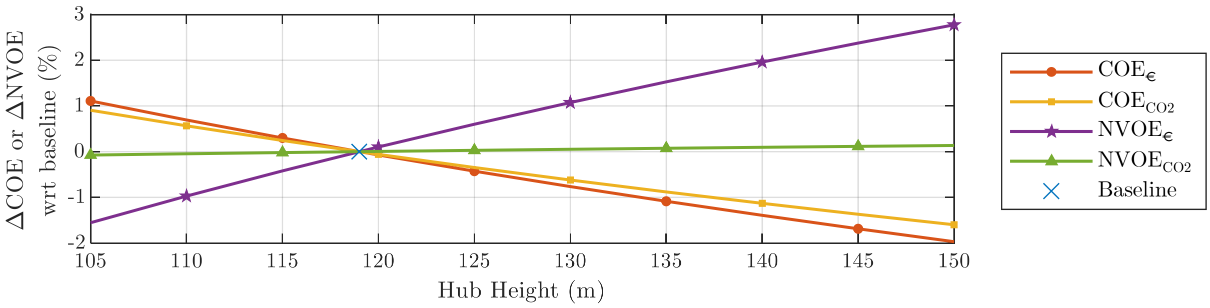

Figure 8. Changes in COE and NVOE with parametrically varying hub height.

265 W/m^2 due to an ideal balance of rotor material demand and energy production, which also results in a maximum for $NVOE_{€}$ with a relative improvement of 2.5% with respect to the baseline. However, $NVOE_{CO2}$ increases further at even lower specific power values. The small relative changes in $NVOE_{CO2}$ are caused by the high mean grid carbon footprint and the associated large displacement of grid greenhouse gas emissions at all wind speeds.

The next analysis involves the variation of the turbine hub height. At the reference site, increasing the hub height results in significantly improved NVOE and COE, as visualized in figure 8. Apparently, the negative impact of a larger amount of material is outperformed by the improved energy production at greater heights above the sea surface. Again, low relative changes in $NVOE_{CO2}$ correspond to the high baseline value.

Finally, the impact of the remaining six technological alternatives on COE and NVOE is analysed in figure 9. A 3-stage high-speed powertrain slightly improves the economic and environmental performance, while a 2-stage medium-speed powertrain causes small gains on the environmental side, but significantly worsens the economic performance. This is because of the balance between remarkable reductions in generator mass, and increased losses and additional mass caused by the use of a gearbox. For high-speed powertrains, the positive effects of a smaller generator outperform the energy losses and the addition of a gearbox. However, medium-speed powertrains experience a negative net balance from the economic perspective.

Lowering the array or export voltage notably increases COE and decreases NVOE due to a larger cable material demand. Five instead of four export cables are required to connect the farm to shore, and many array sections require parallel cabling. In contrast, increasing the cabling voltage improves the environmental and economic performance. This effect is especially pronounced for the export system, where the number of cables is reduced to three. Increasing the array voltage also allows for a reduced number of cables, but results in overdimensioned cabling capacity in many sections, which cancels out most of the benefits.

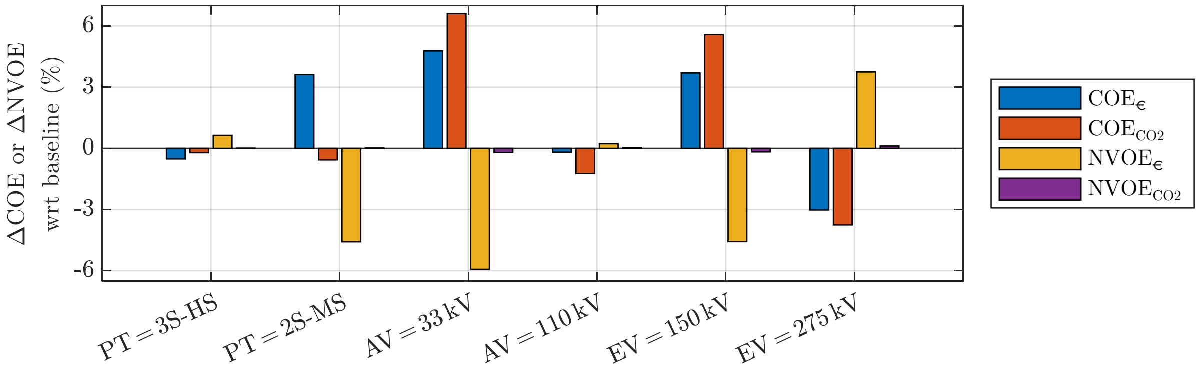

Figure 9. COE and NVOE analysis for different alternatives of powertrain (PT) types, array voltage (AV), and export voltage (EV) with respect to the baseline.

4. Conclusion

This study has showcased the use of the DETECT code for understanding which technological solutions may hold promise for improving the economic and environmental performance of offshore wind farms. While industry already possesses a comprehensive understanding of the choices that enhance the economic viability of offshore wind ventures, this novel framework enables broader evaluations that encompass environmental considerations as well. This allows analysts to highlight possible disparities between the economic and environmental performance, understand their drivers, and facilitate a careful deliberation of possible trade-offs. When applied to the IEA Wind 740-10-MW Reference Offshore Wind Plant with irregular layout, the analysis indicates that a decreased specific power, higher towers, and an increased export voltage level appear to offer great potential for simultaneously improving the economic and environmental performance of the farm. Furthermore, geared high-speed powertrains and an increased array voltage level seem to offer additional minor improvements. Monopiles are confirmed to represent the best economic and environmental technology for the studied reference case.

In general, component production and O&M are driving the economic and environmental COE of the studied wind farm. Steel in nacelle components and the support structure causes most of the emissions, followed by the vessel activities over the lifetime of the farm, which account for a remarkable third of the overall COE_{CO2}. Therefore, more sustainable solutions for steel production and vessel operation are needed in order to drastically reduce the climate change impact of offshore plants.

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