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TNO report

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Cost Model analysis for the electrical integration of floating offshore solar parks with offshore wind parks

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Executive Summary

In this report, a cost modelling analysis of combined offshore floating solar and offshore wind on the North Sea is presented. This analysis is presented as a part of WP7 of the H2020 UNITED project , which focuses on the multi-use of space in offshore wind farms, and investigates the potential benefits of co-use of infrastructure.

This report use a offshore wind farm of 700 MW on the North Sea as test case, and studies three different integration concepts of offshore floating solar of 180 MWp; the SOLO concept, which is integrated at a wind farm substation level, the SEMI concept, which is integrated at an wind turbine array level, and the TOGETHER concept, which is integrated at the individual wind turbine level. These 3 concepts were selected using an earlier multi criteria analysis (MCA), based on cost, flexibility, reliability and environmental impact [1].

The goal of this report is to evaluate the Levelized Cost of Energy (LCOE), Annual Energy Production (AEP), curtailment and space usage of the selected concepts, while examining the sensitivity of the most critical parameters. To this end, the ECN Cost Model is expanded with a floating solar module, and used to evaluate the case study for the 3 concepts.

The analysis shows that:

- The increase in AEP compared to a 700 MW wind farm by itself is 7.2% for all concepts
- The LCOE of the combined system increases by 2 – 5 %, depending on the configuration.
- The curtailment losses from combining offshore wind and solar in this case study are minor, with a maximum of 0.07% of the AEP curtailed.
- The largest share of the cost of the floating solar concepts is from the cables, installation cost and floaters. Conversely, the cost of power electronics (inverters and transformers) has a relatively small impact on the overall cost (<5%).

The TOGETHER concept, integrated on a wind turbine level, was shown to have the smallest increase in LCOE, while providing roughly the same increase in AEP as the other floating solar concepts. Due to its integration with existing infrastructure, it also has the smallest space usage of all three concepts. In short, this analysis shows that currently there is no cost benefit to integrating these concepts, and the gain is instead in the efficiency of area, infrastructure usage and potential for better integration in the energy system, due to lower need for storage.

A sensitivity study was performed due to the lack of experience with floating solar, especially offshore, and resulting high uncertainty in the available data. This analysis showed significant variation in the resulting LCOE, especially in the operational expenditure (OPEX), interest rate and offshore factor. The latter is a metric adapted to quantify the cost of translation of floating solar systems on lakes to an offshore environment. Its sensitivity further highlights the uncertain nature of the calculation, and the need for further study and experience with offshore floating solar.

1 Introduction

Within the Horizon 2020 project UNITED, TNO's work in WP7 is dedicated to the investigation of the electrical integration of floating offshore solar farms with offshore wind farms and the potential benefits of co-use of infrastructure. This report presents the analysis focused on levelized cost, total energy production and efficient use of available space. The latter topic is already a widely studied subject, especially in the North Sea [1]. To this end, a case study was performed where 10 electrical integration concepts were compared using a Multi Criteria Analysis (MCA) [1]. In this MCA, four main factors were compared (cost, flexibility, reliability and environmental impact), with cost found to be the most influential factor. Therefore, the three concepts that scored the most favourable in the MCA are subjected to a cost analysis in this report.

In the case study used for this analysis, a total of 60 wind turbines with a rated of power of 12 MW are installed in a wind park, totalling a nameplate capacity of approximately 700 MW. This production capacity was selected based on all current and upcoming offshore wind farms in the Netherlands, which are typically 700 MW in size, or a multiple thereof [3]. In such wind parks, each array string will host a total of 6 turbines, totalling 72 MW, with a 66 kV cable supporting up to approximately 80 MW [4]. This reference case is constructed without a specific wind (or PV) technology in mind and is therefore technology neutral. In this study, the potential of overloading the cable is excluded, and it is assumed that the installed capacity of the wind farm exactly matches the export capacity. Furthermore, the cost of acquiring space on the North Sea and its impact on other stakeholders, such as loss of fishery grounds and related income, are not considered in this analysis.

A typical profile of offshore wind electrically integrated with a PV farm is investigated in this report[1]. To this end, a PV solar farm is added to the aforementioned wind farm structure with a total peak power of 180 MWp, which is slightly larger than the current largest onshore PV solar farm in the Netherlands [5]. The main components that are used in the PV solar farm are described in Table 1, followed by a description of the three concepts designs that were selected from the MCA. A detailed listing of the components for each concept designed can be found in Appendix E.

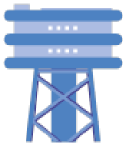
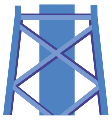
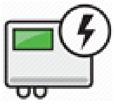
The research questions put forward in this report are:

- What is the expected impact of the integration of floating solar with offshore wind on the levelized cost and annual energy production of offshore energy generation? Which are the most sensitive parameters in this cost?
- What percentage of energy can be expected to be curtailed when combining floating solar and offshore wind on the same electrical connection?
- What is the (normalized) space required for the addition of floating solar to an existing offshore wind farm?

This report is structured in the following way. First, the methodology detailing the cost modelling equations, sensitivity analysis and concept layout is discussed in Chapter 2. Next, the results of the cost analysis and a discussion of the findings is presented in Chapter 3. Finally, conclusions are drawn in Chapter 4.

[1] These profiles are based on aggregated data for Dutch offshore wind and onshore solar from ENTSO-E [23] for 2018, normalized to maximum power production.

Table 1 Overview of the main components of the electrical integration concepts and their symbols.

Title of Component	**Symbol**	**Description of function**
TSO substation		The offshore wind farm or the offshore solar farm or the hybrid farm are connected in this substation in order to transfer power to the nearest shore.
Monopile		A monopile is used as a support structure for equipment such as transformers or inverters.
Transformer		The transformer steps up the AC voltage after the inverter to a higher level (wind farm array or solar farm array)
PV Floater		A PV floater has approximately 15kW of installed capacity. The PV panels are interconnected with cables and the power is transported to the inverter.
Inverter	 S, C,	The inverter (string, central or micro) changes the aggregated DC power from the floaters to AC power.
DC Cable		The DC line transfers DC power between the floaters and the inverter or the switchgear
Wind Farm Array Cable (AC)		The inter-array cable transports AC power between turbines and to the substation
AC Line (PV Farm)		The AC line transport power from solar farms to wind turbines or substation

1.1 Description of the concept investigated

The three concepts analyzed in this report are hereafter presented and described. Based on the results of the Multi Criteria Analysis the following concepts have been selected for the cost model implementation presented in this report:

Concept 1: SOLO – Large solar farm with transformer & inverter integrated on monopile(s), interconnected at the TSO substation where the wind farm is connected

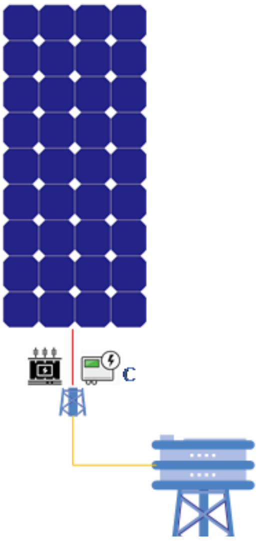


Figure 1 Concept SOLO, visualization of the different components

Description

This concept, as shown in Figure 1, contains approximately 33000 PV floaters, for a total of 180 MWp. The panels on the floaters are connected via DC cabling, with a total length of approx. 120 km, to central inverters, located on monopiles. The output of the central inverters is routed to a central 180 MVA transformer, which transforms the incoming AC power from approx. 1 kV to 66 kV. Afterwards, three 66 kV cables, with a length of 4 km each, are brought from the floating PV farm to the TSO substation. A total of three 66kV cables are used to allow for transport of the full 180 MWp, assuming a cable capacity of 60-80 MVA depending on the configuration.

Concept 2: TOGETHER - Everything DC, with both inverter and transformer on the wind turbine side

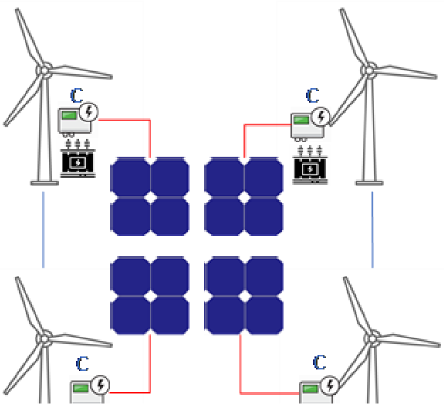


Figure 2 Concept TOGETHER, visualization of the different components

Description

This concept, as shown in Figure 2, has a separate PV field for every other turbine, for a total of thirty 6 MWp fields (18 MWp per wind farm array). In this case, the DC output of the panel (strings) is combined, stepped up to approx. 4-5 kV, and transported using 2 cables to the central inverter, which is located at the wind turbine side. The new transformer, also located on the wind turbine side, is then used to step up the (AC) output to the desired 66 kV.

Concept 3: SEMI - Transformer on a monopile, connected to the wind turbine array

Description

This concept, as shown in Figure 3, is semi-standalone, with a total of 45 MWp per cluster, with a total of 4 clusters making up 180 MWp. For every cluster, the floaters are connected to floating string inverters (225 total). The output of these inverters is combined and routed (via approx. 31 km of cable per cluster) to a central 45 MVA transformer, located on a newly installed monopile. The output of this transformer is fed, via 2 km of 66 kV cable, to the nearest wind turbine to integrate into the array string. The 66kV cable will have a core of 240mm^2, due to its capacity of ~52MVA.

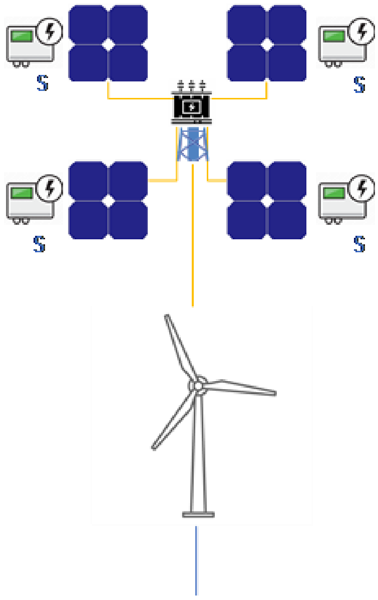


Figure 3 Concept SEMI, visualization of the different components

2 Methodology

This chapter presents the cost model analysis of an integrated large scale offshore wind farm and a floating solar farm in the North sea, based on the three concepts described in Chapter 1. The approach used for constructing the cost analysis is described in Section 2.1. Furthermore, an analysis of the layout and space requirement of the concepts is presented in Section 2.2. Next, the approach to the sensitivity analysis, which is performed to estimate the impact of variation of different equipment, design or circumstances, is described in Section 0. Finally, a detailed summary of equipment cost and related references can be found in Appendix A.

2.1 Cost modelling equations

In this section the specific implementation methodology for the cost model is illustrated and details are referenced. The main parameter resulting from the cost analysis is the levelized cost of electricity (LCOE), which is presented in Section 2.1.1. Furthermore, the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX) are illustrated with a detailed analysis in Section 2.1.2 and Section 2.1.4, respectively. After this, an overview of the Annual Energy Production (AEP) calculation is presented in Section 2.1.5. Finally, the approach to calculating the expected curtailment loss is discussed in Section 2.1.6.

2.1.1 LCOE calculation

In order to show the impact of the floating solar farm on the cost of the wind farm, a percentage change is calculated. Therefore, the levelized cost of electricity (LCOE) from the reference wind farm of 700MW is related to the total cost of the new integrated system. The comparison equation can be expressed as follows:

$$\%difference = \left(\frac{LCOE_{concept}}{LCOE_{reference}} - 1\right) \cdot 100\%$$

The different final LCOEs also contain the cost of electrical infrastructure $LCOE_{e\text{-}infra}$, which is all the costs from the substation and cabling up until the onshore connection to the transmission grid. This $LCOE_{e\text{-}infra}$ does not consider OPEX, since it is assumed to be part of the wind and solar OPEX. Additionally, the wind annuity a_{wind} is used for this calculation.

$$LCOE_{reference}\left[\frac{€}{MWh}\right] = LCOE_{windfarm} + LCOE_{e-infra}$$

$$LCOE_{concept}\left[\frac{€}{MWh}\right] = LCOE_{combinedfarm} + LCOE_{e-infra}$$

$$LCOE_{e-infra}\left[\frac{€}{MWh}\right] = \frac{\left(\frac{CAPEX_{substationuntilonshore}}{a_{wind}}\right)}{AEP_{combinedfarm}}$$

The $LCOE_{windfarm}$ is the cost of electricity of the reference wind farm which is calculated based on TNO's Python wrapper Cost Model code [6]. The Annual Electricity Production (AEP) is based on Cost Model calculations, as discussed in Section 2.1.5.

$$LCOE_{windfarm}\left[\frac{€}{MWh}\right]=\frac{\left(\frac{CAPEX_{windfarm}}{a_{wind}}\right)+OPEX_{windfarm}}{AEP_{windfarm}}$$

The same formula is applied to calculate the $LCOE_{solarfarm}$, with the solar annuity a_{solar} used.

$$LCOE_{solarfarm}\left[\frac{€}{MWh}\right]=\frac{\left(\frac{CAPEX_{solarfarm}}{a_{solar}}\right)+OPEX_{solarfarm}}{AEP_{solarfarm}}$$

For the $LCOE_{combinedfarm}$, the LCOE of the offshore wind and floating solar farm are summed up:

$$LCOE_{combinedfarm}\left[\frac{€}{MWh}\right]=\frac{\left(\frac{CAPEX_{windfarm}}{a_{wind}}\right)+OPEX_{windfarm}+\left(\frac{CAPEX_{solarfarm}}{a_{solar}}\right)+OPEX_{solarfarm}}{AEP_{combined}}$$

2.1.2 Capital Expenditure (CAPEX) calculation

The $CAPEX_{windfarm}$ is the sum of all component costs of the wind farm up until to the connection to the TenneT substation including logistics and installation cost. These costs are estimated in the Cost Model TNO Python Wrapper, and the different parts are the following:

$$CAPEX_{windfarm}[€]=C_{turbines}+C_{monopiles}+C_{installation}+C_{electrical}$$

Within the Cost Model Python Wrapper, the unmodified cost components are $C_{turbines}$, $C_{monopiles}$ (*except potentially the J-tube modifications*) and $C_{installation}$.
The $C_{electrical}$ is broken into the following parts: the cost of the in-field CAPEX which are the string cables and the transformers, and the cost of the power export which is the transmission costs including the substation, cabling to shore and other equipment needed.

The $CAPEX_{solarfarm}$ contains the sum of all the cost of the components of the solar floating farm up to the connection either to the wind farm infrastructure or assets or the connection to the TenneT substation. The CAPEX also includes the installation cost, which differs per concept. For example, a stand-alone floating solar farm would need to lay all cables up to the point of TenneT substation, while a concept that uses the existing wind farm infrastructure would benefit from not having to invest in extra cables or other electrical infrastructure. For this analysis the installation costs are based on the floating solar farm installation costs on lakes and multiplied for an offshore factor. The detailed equation for the $CAPEX_{solarfarm}$ is shown below:

$$CAPEX_{solarfarm}[€]=C_{PV}+C_{inverters}+C_{transformer}+C_{j-tube}+C_{installation}+C_{monopile}+C_{cables}$$

The different components that have now been identified for the solar farm are presented in Appendix A, the detailed cost investigation for each components and its reference are illustrated in Table 2.
The C_{PV} contains the CAPEX cost of the PV modules and the floaters, anchors and mooring lines. Regarding the mooring lines, a presentation at SolarPlaza [6] showed an approximation of ~30 mooring lines/MWp for lake floating solar farms.

$$C_{PV}[€]=C_{solarpanels}+C_{floaters}+C_{mooringlines}$$

The $C_{inverters}$ contains all the capital expenditures for the inverters that would be needed for the floating solar farm. The $C_{transformer}$ contains all the capital expenditures related to the transformers that step-up the power to reach the sufficient medium voltage level required to reach the substation [7].

The $C_{monopile}$ contains all CAPEX related to the monopile(s) that will support the electrical infrastructure for the floating solar farm (transformers in the SOLO concept). Transportation and installation costs should be included as well. A good first approach comes from the OWECOP [7] model and Upwind model [8], after an extensive discussion with the TNO team specialized in structure and monopile, the cost for an offshore wind turbine structure are translated to the solar farm divided by 2.

$$C_{monopile}[€] = CAPEX_{monopile} + Transport + Installation$$

The $C_{j\text{-}tube}$ contains all CAPEX needed to (retro)fit wind turbines to host additional cables towards their switchgear coming from the PV clusters. This assumes the addition of 1 j-tube at each last turbine of the 4 strings were it would be interconnected for the SEMI concept, or the addition of 30 j-tubes at each turbine for the TOGETHER concept [9].

$$C_{j-tube}[€] = CAPEX + Installation + OPEX$$

The C_{cables} contains all the capital expenditures related to the cabling required to interconnect the PV modules on the floaters thus creating strings, the dynamic cables (floating in the sea) which interconnect clusters of floaters or interconnect clusters to a wind turbine level or wind farm substation level, and finally the (new) array cables needed to transfer all power to the TenneT substation.

$$C_{cables}[€] = C_{moduleinterconnectioncost} + C_{dynamiccablesforfloaters} + C_{arraycables}$$

It is assumed that a similar 66kV cable design is made for solar farms as well [10]. The report suggests the following array cable costs per meter and a ball-park estimation of installation cost of 200-400 euros per installed meter, see Table 2.

$$C_{moduleinterconnection}[€] = C_{LVcablecost} + C_{installationcost}$$
$$C_{arraycables}\ [€] = C_{arraycablecost} + C_{installationcost}$$
$$C_{dynamiccables}\ [€] = C_{dynamiccablecost} + C_{installationcost}$$

Table 2 66 kV and 33 kV array cable costs [10]

Cost per meter [€]	**System Voltage**			
	66 kV		**33 kV**	
	630 mm^2	**240 mm^2**	**800 mm^2**	**240mm^2**
Low	386	182	420	165
Medium	425	200	465	180
High	468	220	515	200

The $C_{installation}$ cost component is modelled with cost function equations from references [11]. For this analysis, the following equation is applied, based on literature review and assuming an offshore factor which is explain in the next section.

$$C_{installation}[€] = C_{installation_{FPV_{lakes}}} * \eta_{offshorefactor}$$

2.1.3 Annuity

The CAPEX costs are divided by the annuity factor. This allows to calculate the annual cost due to CAPEX, as the OPEX and the AEP are given on an annual basis. The annuity factor is calculated as follow:

$$a_{wind} = \frac{(1-(1-r_{wind})^{-n})}{r_{wind}}$$
$$a_{solar} = \frac{(1-(1-r_{solar})^{-n})}{r_{solar}}$$

Where *r* is the interest rate and *n* represents the life time of the wind farm and of the solar farm in years. In this study the interest rate is assumed to be 2.5% and the life time is assumed to be 25 year for both systems.

2.1.4 Operational Expenditure (OPEX) calculation

For the $OPEX_{windfarm}$, a TNO Wind model is used that can predict the costs for the lifetime of the offshore wind project, but for the solar floating farm and due to lack of operational experience, an equation is set-up. This equation contains 2 factors:

- $\eta_{offshorefactor}$ [%]: percentage increase of the normal operational expenses from experience from either land-based utility scale PV installations or floating (lake) installations. This percentage includes offset-factors (compensation for transportation of installation of equipment necessary and other materials offshore), more skilled personnel, environmental resources unavailability (large waves causing delays). The rationale behind those factors is inspired and explained in [12].
- $\eta_{reductionduetocombination}$[%]: percentage change from potential savings due to combination with offshore wind farm activities.

$$OPEX_{solarfarm}[€] = OPEX_{solarfarm} * \eta_{offshorefactor} * \eta_{reductionduetocombination}$$

The $OPEX_{windfarm}$ is based on all repair activities necessary to be performed at the wind farm level, and it is extracted from a simplified equation based on a TNO O&M tool. The $OPEX_{solarfarm}$ is based on all the corrective and preventive maintenance activities to be performed for the solar farm. As described earlier an offshore factor is added with respect to O&M activities to either land-based or lake floating PV system concepts. The O&M costs are obtained from literature and interview sessions with experts from TNO and Oceans of Energy. The floating solar farm OPEX is based on a technology factsheet from TNO [13]. Next to the offshore factor, an integration reduction factor is applied, as there's intention to combine O&M activities of solar and wind farm so as to reduce double counting transportation costs (Crew Transfer Vessel costs) to the offshore location and thus some savings are applied. These synergies are hard to quantify and therefore some assumptions need to be taken into account prior.

2.1.5 Annual Electricity Production (AEP) calculation

The $AEP_{combinedfarm}$, is the sum of both the generated electricity from the wind farm and the solar farm including all possible modelling factors.

$$AEP_{combined}\ [MWh] = AEP_{windfarm} + AEP_{solarfarm}$$

For the $AEP_{windfarm}$, there's a dedicated electricity model in Cost Model, which gives us the total sum throughout the year including as well availability losses(%), which are assumed 6%. The annual energy production is estimated with a given time series for a specific location in the North Sea, which in this study is selected to be the Borssele wind farm. The time series include the wind speed and direction at a certain height and are corrected to the hub height, based on a wind shear. An assumption of a generic wind farm configuration is made where a wind farm power curve is constructed with a generic wake loss estimation. An interpolation is then made between the 2 tables in order to determine at each timestep the resulting wind farm power production. This is later summed up for the whole wind farm lifetime and corrected with the availability losses. The $AEP_{windfarm}$ then becomes:

$$AEP_{windfarm}\ [MWh] = P_{nominalwind} * cf_{wind} * 8760\ [h]$$

where:

- $P_{nominalwind}$ is the rated wind power [MW],
- cf_{wind} is the expected capacity factor of the wind farm, including availability losses [%].

For the $AEP_{solarfarm}$, a simplified equation is set-up taking into consideration:

- the nominal power of the solar farm, $P_{nominalsolar}\ [MW]$,
- the expected potential capacity factor of the solar system, cf_{solar} [%],
- other offshore related efficiency factors (water cooling, less soiling than land-based etc.) and
- the curtailment losses due to common utilization of electrical carrying capacity components (e.g. wind turbine array cable), $\eta_{curtailment\ due\ to\ integration}$ [%].

$$AEP_{solarfarm}\ [MWh] = P_{nominalsolar} * cf_{solar} * 8760\ [h] * \eta_{curtailment\ due\ to\ integration}$$

The cf_{solar} is assumed based on the available literature. From the Renewable Energy Statistic 2020, IRENA, the Netherlands in 2018 had a capacity installed of 4522 MWp and a total annual energy production of 3693 GWh from which a CF of 9.3% can be extracted, up from 8.7% in 2016 and 8,9% in 2017 [12]. Several studies have investigating the performance of floating photovoltaic systems, as the temperature of the water acts as natural cooling system for the PV, which strongly increases its efficiency. It has been observed to decrease the temperature between 5 and 10℃ compared to systems installed on a roof. A study from Utrecht University simulated a floating system onshore and a floating system on the North sea, and noted an increase of its annual energy production by 12.96% reaching 18% in the summer months. [14]. Furthermore, in the public report from the World Bank on the floating solar PV market, a general gain in the energy yield between 5 and 10% is estimated, although it underlines the need of further investigation, as FPV is still a novel technology and empirical data is missing [15]. Based on this literature review, it is assumed that the capacity factor is 15% for a future floating offshore solar farm.

2.1.6 Energy curtailment calculation

When infrastructure is shared between a solar and the wind farm without altering the existing infrastructure, there is potential for curtailment being required due to limited capacity of the transport infrastructure (usually cables). This effect is a direct loss of energy, and is classified as $\eta_{curtailment\ due\ to\ integration}$ in this analysis. An estimation of this effect is performed by combining typical PV and wind production time series, and calculating the lost energy from the total production above the rated cable transport capacity. This lost energy is then expressed as a percentage of the total energy production, and used to correct the AEP, as explained in Section 2.1.5.

There are several stages in the connection chain where curtailment may be required, which differs between the concepts. Specifically, the transport infrastructure may be limited at the substation (export cable) level, the array (cable) level, and the wind turbine (transformer) level.

An overview of the estimated curtailment at each of these levels is presented in Table 3, indicating losses as a percentage of the (combined) AEP.

Table 3: Expected curtailment loss at different stages of the electrical infrastructure, in % of AEP.

Concept	Estimated curtailment required at each level [%]			
	Substation	**Array**	**Turbine**	**Total**
SOLO (#1)	0.05	n.a.	n.a.	0.05
TOGETHER (#2)	0.05	-	-	0.07
SEMI (#3)	0.01	0.06	n.a.	0.05

This overview clearly shows how both the SOLO and TOGETHER concept are substation limited, while the SEMI concept is mainly array limited. The TOGETHER concept is not limited at the turbine level due to usage of a new transformer instead of an existing one. It's also not limited at the array level, due to all clusters being distributed over the wind farm, which can be supported by the array cable. In all cases, the expected curtailment (and its impact) is minor, as will be discussed further in Chapter 3.

2.2 Electrical integration concept layout and space

The layout of the three selected concepts is studied in more detail for the cost analysis, in order to get a complete estimate of the cost, rather than a comparative one as used in the MCA. To this end, the entire chain of components, in particular the cabling, was recalculated, leading to the estimated cable lengths shown in Table 4.

Table 4: Estimated cable lengths for assumed layouts, for each concept and cable type.

Concept	Estimated cable length [km]			
	PV(DC)	**LVAC**	**MVDC**	**66 kV**
SOLO (#1)	389	67	-	18
TOGETHER (#2)	213	-	15	-
SEMI (#3)	64.8	126.4	-	8

These cable lengths were calculated from newly constructed layouts for each selected concepts. The changes with respect to the MCA layouts include re-evaluation of spacing between strings to better allow O&M access, and a common (floater) PV building block for each of the three concepts. Using these newly calculated layouts, the required area for each concept was evaluated, as shown in Table 5. The schematics depicting these new concept layouts are presented in Appendix B, 0, and 0.

Table 5: Estimated length, width and area requirement for assumed layouts, for each concept.

Concept	Estimated space requirement (total)		
	Length [km]	**Width [km]**	**Area [km²]**
SOLO (#1)	11.8	0.94	11.1
TOGETHER (#2)	0.68 (x30)	0.25 (x30)	5.2
SEMI (#3)	1.71 (x4)	1.2 (x4)	8.2

2.3. Sensitivity analysis approach

As described in the previous sections, the implementation of the Cost model for floating solar farm is based on an extensive literature review on the costs of the different equipment, installation, O&M and integration of the two systems. Nevertheless, the novel technology still requires several assumptions for different parameters as empirical data is not available. For this reason a sensitivity analysis is realized on several parameters. In this section, the sensitivity analysis is illustrated, describing the reason and the values for each concept. The parameters selected for the analysis are the ones most influential on the output cost, or the ones based on strong assumptions, as reference or literature is still unavailable.

A detailed description of the different components contribution in the CAPEX of the PV solar farm is illustrated in Figure 4. Floaters (including PV panels), cables and installations are the three major components affecting the CAPEX costs for all concepts. In particular, cables contribute to more than 50% of the total CAPEX in the SOLO concept, and 43% in the SEMI concept.

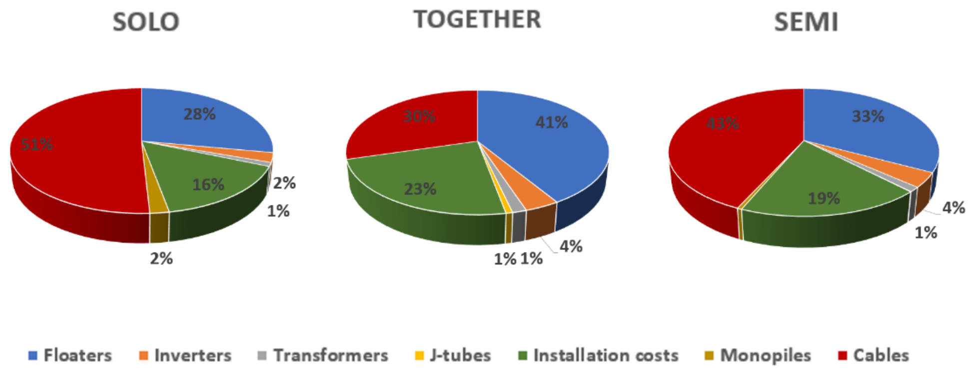


Figure 4 CAPEX breakdown for each concept: SOLO (left), TOGETHER (centre) and SEMI (right)

2.2.1 Sensitivity scenarios

The following list illustrates the sensitivity analysis scenarios selected in this analysis.

With respect to CAPEX:

- The floater costs: floaters have currently been installed on lakes, which are characterized by low wind, small waves and fresh water, these environmental conditions change for floaters on the open sea, which application is still on a pilot stage with few examples and which require resistance to much harsher condition, with strong winds, high waves and salty water. For these reasons, a cost estimation is based on literature available for lakes application and on assumption of cost increasing with fixed ratio $\eta_{offshorefactor}$, as explained in section 2.1, due to sea conditions is applied. Furthermore, after a first analysis it was observed that the floaters cost extensively contributes to the total CAPEX, in total around 25-35%. The cost of the floater is simulated in a range between a low scenario with the cost lowered by 25% and a high scenario with the cost increased by 25%.

- The cable costs: the cables layout has been designed for the different scenario with real layout size to obtain a feasible estimation of the cables needed for each scenario. As it is still an early stage simulation, the design can be remodeled and the layout and length of cables can change strongly. Therefore, total cable cost is considered an uncertain assumption. Furthermore, cable costs have a high share in the CAPEX costs, up to over half of the total

CAPEX. For each concept, which is defined by a different combination of cables type and length, each cable type is simulated between a low scenario with its costs reduced by 25% and an high scenario where costs are increased by 25%. Finally a combined scenario is further simulated where the combination of all the cable costs reduction or increase are combined together providing a total low and high scenario where all cables are simulated in the same case.

With respect to OPEX:
- The OPEX: The OPEX cost itself is also simulated within different range. It represents a small percentage of costs comparing the CAPEX costs (%), but it is again based on assumption as offshore floating solar represents a novel technology with a lack of experience from industries. The OPEX cost is therefore simulated for three scenarios, a low with the OPEX cost reduced by 25%, a high scenario with OPEX costs increased by 25% and an highest one with an increased by 100% of the costs.

- The offshore factor: it is applied for the OPEX costs and for the installation costs. As a reference for a floating offshore solar farm is not available, the literature for lakes application is adapted and assumed for the sea condition applying an offshore factor. This factor increases the O&M and installation costs for lakes application. The base case assumes a offshore factor of 1.5; the low scenario simulates an offshore factor of 1, the high scenario of 2 and an extreme scenario with offshore factor of 4 is also simulated.

With respect to overall economics:
- For the annuity factor, the sensitivity analysis is made on the interest rate. For the aforementioned reasons of unavailable reference and literature, the base case scenario of 2.5% interest rate is simulated to 1% for the low scenario and for the high scenario of 5%.

3 Results & Discussion

This section presents the results of the three selected electrical integration concepts simulations, along with the sensitivity analysis.

The main results are illustrated in Table 6, which shows the LCOE, AEP, curtailment loss and area requirement of the three studied concepts.

The LCOE comparison is computed through the model implementing the different concepts. The variation of the LCOE has been provided in % value to illustrate the sensitivity of the LCOE to the different layouts. The $LCOE_{concept}$ is higher than the $LCOE_{reference}$, mainly due to the higher cost of the PV solar farm and its lower capacity factor. In specific, the SOLO concept is the one which increases the LCOE the most, approximately by 5% of the total LCOE, whereas the TOGETHER concept increases the LCOE by approximately 2%. The SEMI concept increases the total LCOE by approximately 3.5%. Furthermore, adding the PV solar farm to the offshore wind farm production increases the AEP slightly: for all concepts, the AEP increases by just over 7%.

In addition, a comparison on the total area needed by each concept is also presented, which can be valuable when investigating the space availability for integration of different systems within the natural environment. The details of the area requirements per concept are analyzed in Section 2.2, with illustrations presented in the Appendix B-D. The SOLO concept needs around double of the space covered in comparison to the TOGETHER concept, whereas the SEMI design requires an area in between the TOGETHER and SOLO ones.

Table 6 Results of the cost model analysis for each of the concepts investigated.

	Concept 1 (SOLO)	**Concept 2 (TOGETHER)**	**Concept 3 (SEMI)**
$LCOE_{concept} / LCOE_{reference}$	N/A*	N/A*	N/A*
$AEP_{concept} / AEP_{reference}$	N/A	N/A	N/A
Curtailment losses of combined system due to integration (%)	N/A	N/A	N/A
Concept area requirement ($km^2/MW_{installed}$)	N/A	N/A	N/A

*** For confidentiality reasons, certain values have been excluded from the table. For more detailed information or inquiries regarding the excluded data, please contact the first author.**

3.1 Sensitivity results

The results from the sensitivity analysis are presented in this section by concept. The following table presents the range of variation in the LCOE of the solar farm between the low and the high scenario compared to the base case of each concept.

Table 7: Sensitivity results of the LCOE of the floating solar farm for each concept.

	LCOE Solar		
Concept	**SOLO (%)**	**TOGETHER (%)**	**SEMI (%)**
Floater	+/- 6	+/- 7	+/- 6
Cable	+/-10	+/-5	+/-8
OPEX	+/-5	+/-7	+/-6
Offshore factor	+/-11	+/-15	+/-13
Interest rate	-13/+24	-12/+22	-12/+23

The main outcomes of the sensitivity study are summarized below:

- By assessing the totals section on the right of the table, it is observed that the $LCOE_{combined}$ of these concepts is always more expensive than the reference $LCOE_{wind}$ (first row for each concept), even in the low sensitivity ranges.
- The most sensitive parameter is the offshore factor, which is also the one which lacks literature and references.
- The OPEX, which is based on significant assumptions due to lack of data and experience, has a medium impact on the LCOE combined costs, mostly due to the assumed doubling of the cost in the high scenario.
- Similar results to the OPEX analysis are produced by the interest rate variations, mostly due to significant differences in the sensitivity cases.
- The cable costs remain a significant component affecting the CAPEX, even in case of the lower cost assumed in the low scenario
- The floaters have a relatively small impact on the LCOE between the different scenarios, with the biggest impact observed in the TOGETHER concept.

4 Conclusions and Recommendations

In this report, a cost model for an offshore integrated floating solar and wind farm was developed and used to study three integration concepts. These integration concepts were selected as most promising from a total of 10 in a multi criteria analysis (MCA), based on their expected cost, flexibility, reliability and environmental impact. The cost analysis of the MCA was further detailed in this report, using data from available literature and experts on floating solar to estimate the impact on the combined LCOE, AEP, curtailment and space usage. In addition, a sensitivity analysis was performed, in an attempt to identify critical assumptions and uncertainties.

The preliminary results of the cost modelling show that the expected increase in AEP is approximately 7.2% for all concepts. At the same time, the LCOE of the combined system is expected to increase by between 2 – 5 %, depending on the configuration. The curtailment losses expected from combining offshore wind and solar in this case study are minor, with a maximum of 0.07% of the AEP curtailed. From the CAPEX breakdown, it can be observed that the largest share of the cost is from the cables, installation cost and floaters. Conversely, the cost of power electronics (inverters and transformers) is expected to have a relatively small impact on the overall cost (<5%).

Based on the large uncertainties and lack of practical experience in some of the assumptions for the cost modelling, it was decided to perform a sensitivity analysis. This analysis highlighted the large uncertainty in the results, due to the large variations that were observed from varying the offshore factor. In addition, the cable cost was again seen to have a large impact on the LCOE of the combined system, even if in case the unit cost of a cable is lower than expected.

From the three concepts that were studied in this report, the TOGETHER concept was shown to have the smallest increase in LCOE, while providing roughly the same increase in AEP as the other concepts. Due to its integration with existing infrastructure, it also has the smallest space usage of all three concepts. However, it is clear that the integration on a turbine level does lead to relatively more curtailment losses compared to the concepts that are integrated on an array or substation level.

Due to these results and the cable cost contributing to >30% of the overall cost in all concepts, it is recommended to pay attention to the design of the offshore solar farm, particularly the layout, which has a large effect on the cable length and therefore cost. Furthermore, the floating solar cost modelling currently contains a lot of uncertainties due to the lack of available data and experience, particularly on the O&M and installation cost. Therefore, it is recommended to refine these models once more accurate data and experience has been obtained. Finally, the interaction of the wind farm and floating solar farm needs more detailed study, especially in the case of shared use of infrastructure, such as in the TOGETHER concept.

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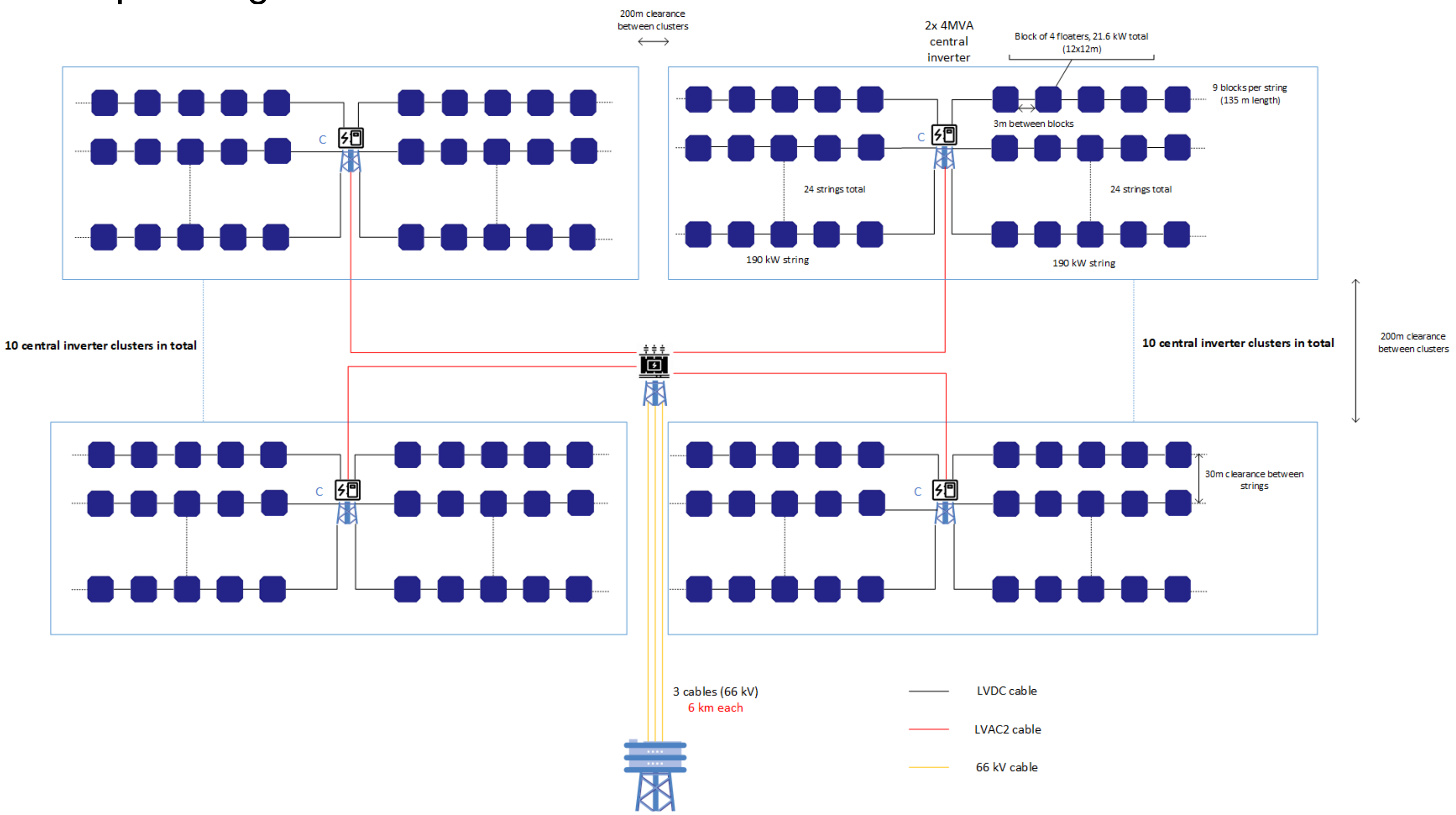
A. Equipment cost

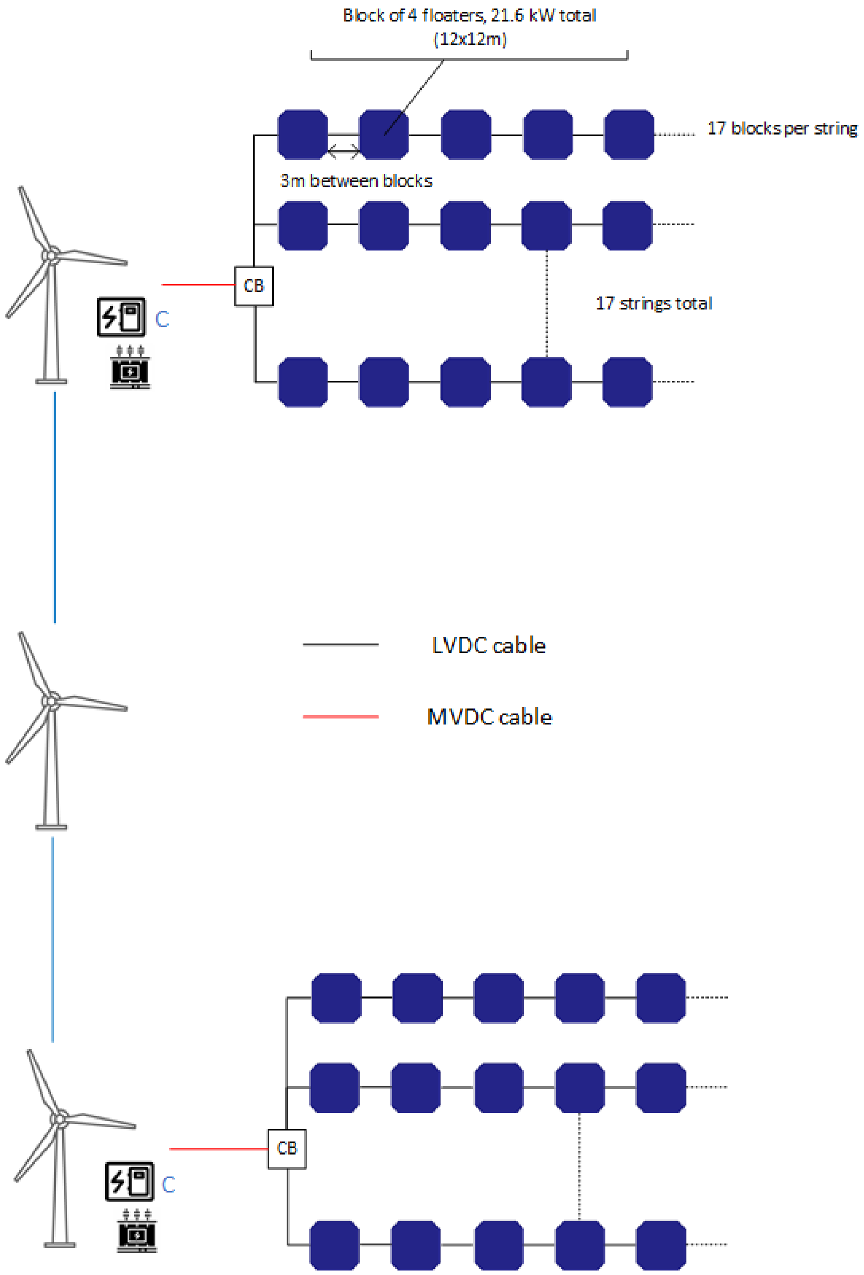
Table 8 Summary of the capital and operational expenditures expected for the different equipment

Equipment	Type	Cost €	Info	Lifetime	Reference	Concept
PV	Floater	0.3-0.4/Wp	Min-Max	-/-	Table 7 in section 4.4. in [16]. ECN cost study on floating (South orientation) [13] and (East-West orientation) [17]	All
Inverters	String	45/kW	Most likely replaced, not repaired	5-14y	[18], DNV PV Inverter Useful Life Considerations [19]	SEMI
	Central	35/kW	10y in harsh environment	10y–25 y		SOLO, TOGETHER
Monopile	-/-	500000	Assumed based on Wind prices	-/-	OWECOP [8]	SEMI
Transformer	WT new	85200	Price per unit	-/-	OWECOP , [7]	SOLO, TOGETHER
	Central	2556000 639000	180MVA (SOLO) 45 MVA (SEMI)	-/-	OWECOP , [7]	SEMI
Cables	PVDC	100/m	Installation is assumed to be ~€300/m	-/-	[20]	All
	MVDC	400/m		-/-	Assumed to be same as LVAC	TOGETHER
	LVAC	400/m	Installation assumed to be ~€300/m	-/-	[21]	SOLO, SEMI
	66kV	500/m		-/-	66 kV Systems for Offshore Wind Farms [4] 33kV ~ 40MW, 66kV ~ 80MW through a 630mm² cable (copper) [22]	SOLO, SEMI
J-tube	-/-	40000	If build it from the start.	-/-	OWECOP [8]	TOGETHER, SEMI
OPEX	-/-	0.0139 M€/MWp	Based on floating solar - lake (projected for 2030)	-/-	ECN cost study on floating solar (South orientation) [13]	All

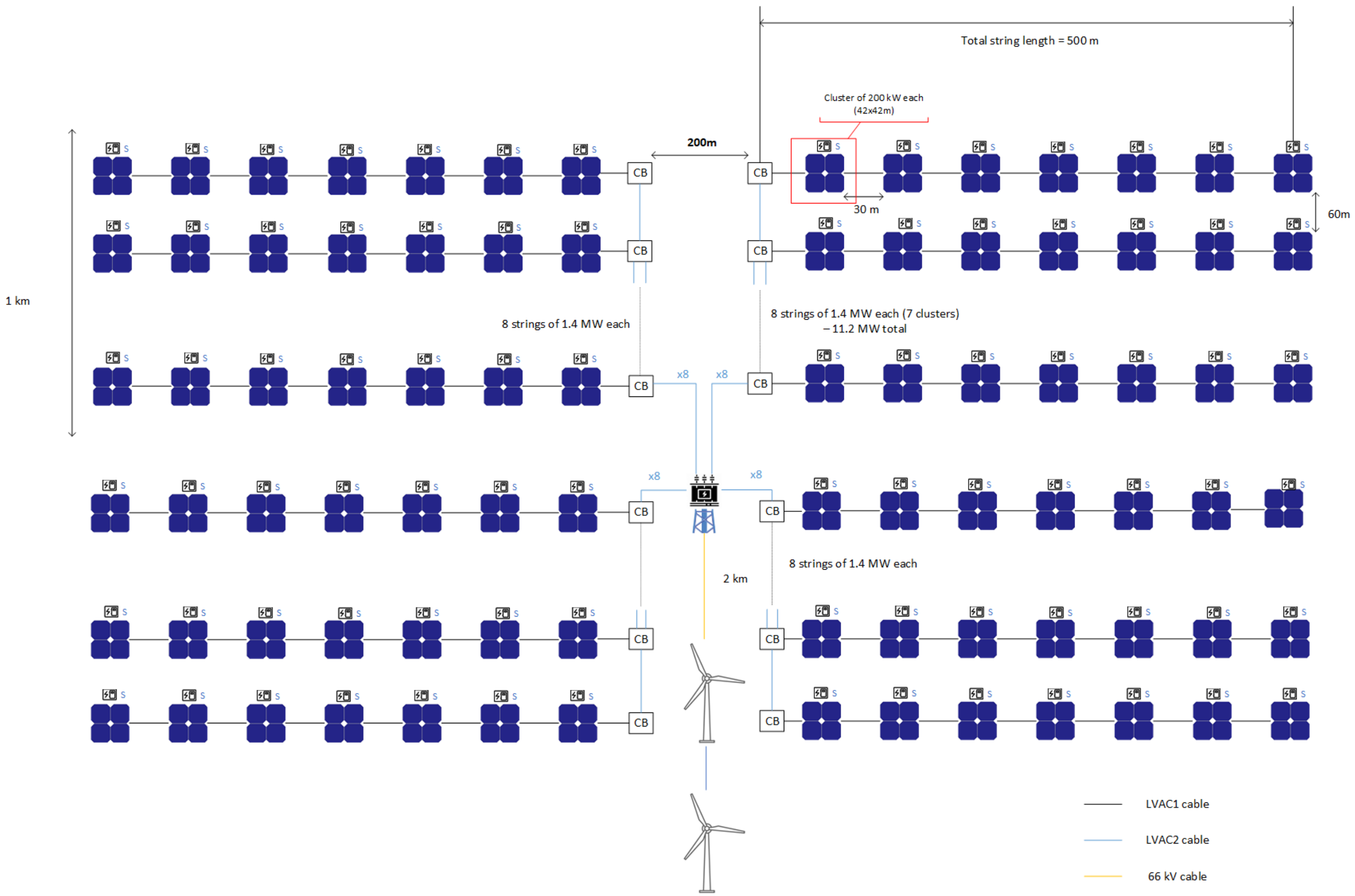
B. Concept configuration - SOLO



C. Concept configuration – TOGETHER



D. Concept configuration – SEMI



E. Concept configurations

Table 9 Summary of the components for each concept. Note System organization represents the number of cluster, therefore each element has to be multiplied by the number of System organization unit.

Equipment	**Type**	**Unit**	**SOLO**	**TOGETHER**	**SEMI**
PV	Floater (5.4kWp)	Units	33000	1100	8250
System	*Organization*	*Units x MW*	*1x180*	*30x6*	*4x45*
	Cluster Area	*m^2*	11.1 km^2 (11.8x0.94)	*0.17 km^2 (0.68x0.25)*	*2.05 km^2 (1.71x1.2)*
Inverters	String	Units			225
	Central	Units	20	1	
Monopile		Units	20		1
Transformer	WT existing	Units			
	WT new	Units		1	
	Central	Units	4		1
Cables	PVDC	km	389	7.1	16.2
	LVAC	km	67	-	31.6
	MVDC	km	-	0.5	-
	66kV	km	18	-	2
J-tube		Units		1	1