24th International Conference on Renewable Energies and Power Quality (ICREPQ'26)
Santander (Spain), 10th to 12th June 2026
ISBN-13: 978-84-09-82044-3

A Novel Method for Optimizing Offshore Substation Installation and Commissioning for Offshore Wind Projects

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Abstract

Renewable energy, particularly offshore wind projects, has been a key focus for utility companies and developers over the past 15 years [1]. Organizations with extensive experience in power generation have increasingly pursued the concept of harnessing energy from marine environments. While the capital investment for offshore wind farms is significantly higher than for other power generation installations of similar capacity, studies indicate that wind resources in some regions offer greater stability and higher energy yield, enhancing long-term viability and efficiency [1].

The risks in the offshore wind projects can affect the construction, commissioning, operation, and maintenance, and directly impact the viability of a profitable business case. Consequently, adopting a robust methodology that systematically accounts for these risks is critical to ensuring the project's financial sustainability.

Therefore, the purpose is to identify risks during an important part of the installation and commissioning of offshore wind projects and develop a methodology to mitigate them. Based on the risk identification, this methodology explores the different phases of the project where the mitigations can be implemented to avoid any future delay in the project. The method proposes mitigations depending on different factors, such as weather, environmental conditions, seasons of the year, logistic availability, and other factors that affect the success of the project.

Results indicate areas of time improvement during the activities of the project, due to logistical enhancements, environmental mitigation, and commissioning completion in different timelines of the project, an approach unprecedented in this sector, and help to develop offshore wind energy.

Keywords. Offshore wind farm, Mechanical and Electrical installation (M&E), Offshore substation, Risk Mitigation, Weather downtime.

1. Introduction

These projects require comprehensive studies for the installation and implementation of specific measures and initial risk analysis of the installations and their respective mitigations before the activities commence. There is some scientific literature about the risks and mitigations to be done, but none proposes a clear methodology with the different phases and the problems to be solved sequentially. Gatzert et at. proposed an interesting analysis, [2]of the different risks and some mitigations of Offshore Wind Projects implementation, but not directly in the sequence or schedule of works.

Another challenge in the overall offshore wind business is that the different suppliers of wind turbine generators have developed new turbines, intending to pursue an increase in power generation to the design limits [3]. The reason is that the offshore market has been moving in this direction in recent years, for developers to install turbines with higher production so they can better optimize their investments and increase their rate of return, making projects more financially attractive and sustainable over the long term[4].

This affect the incrementality of the size of the equipment, robustness of the material, and projects with much more production capacity, where offshore substations must have reliable systems and much bigger dimensions due to the increase in power capacity installed, playing a key role as the point of interconnection between the strings of the wind turbines and the onshore substation through the high voltage export cables.

A key factor in research is the impact on the project schedule. When determining the quantity for completion of offshore works, there is a need for a certain quantity of labour workforce due to the bunch of activities to be executed offshore, rather than those finalized before the substation sail-away from the onshore facility. It increases the risk of construction and completion offshore[2],

Another factor identified after reviewing the existing literature is the lack of detailed studies addressing risks and mitigation measures during the installation and commissioning phases of offshore substations for wind projects[2]. In particular, there is limited analysis of how these phases are affected by weather downtime, crew logistics strategies, environmental impacts across different project stages, and the implications of completing commissioning activities prior to the execution of certain offshore works.

The rest of the paper is organized as follows: Section 2 presents the material and method of the study, Section 3 describes the case study, and Section 4 provides the results. Finally, the paper's conclusions and discussion of the research are outlined in section 5.

2. Material and method

This research presents a novel methodology to analyse the activities and different options to be applied for the offshore substation of a wind farm project with the goal of improving the schedule of activities for the installation offshore, completion of the works, commissioning, energization, and interim commissioning, and therefore the finalization and taking over of the project to achieve the commercial operation. This method is replicable and scalable to any case study.

The completion of the offshore substation, including both construction and commissioning, is a critical path activity for the project, as it is essential for supplying power to the wind turbines to finalize their commissioning and enable the project to commence energy production, thereby contributing to the achievement of a positive business case.

This research is focused on the sail away, which is the transportation of the offshore substation from the origin port to the wind development area where the final installation is taking place, together with commissioning and interim maintenance till commercial operation.

For the mentioned activities, the **quantity of remaining work** and **logistics** play a critical role in the offshore substation being energized.

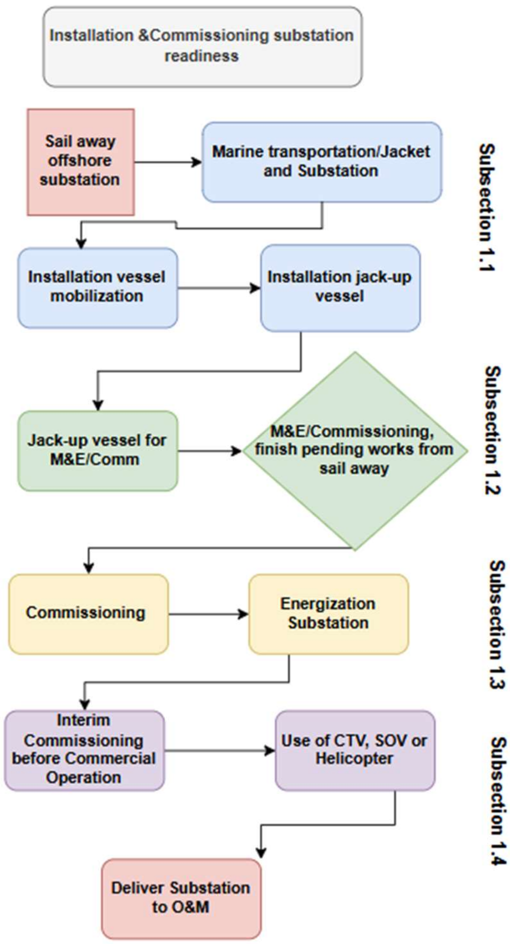
This research presents several process optimizations, with the aim of highlighting possible measures to apply to the project that can be implemented to avoid any delay in the commencement of the energization process and the entire commissioning.

By analysing the percentage of work remaining prior to sail-away, identifying the substation systems to be prioritized, and considering the impact of the labour workforce in the United States—particularly due to limited offshore experience—all these factors should be taken into consideration for a successful project.

Adding to the previous factors, and no less important, is to assess and identify the most suitable access and logistic strategy for the offshore substation during the interim commissioning phase, before formal handover to the Operations and Maintenance team.

Figure 1: The flowchart represents the proposed methodology, which helps us gain a clearer understanding of the different subsections and the options to find the best solutions to the different risks and to choose the best route to mitigate them. Several clearly defined phases can be identified:

• Sail away and installation vs weather. Subsection 1.1 (blue).
• Mechanical and Electrical (M&E) readiness before sailing away. Subsection 1.2 (green).
• Energization through completion of commissioning. Subsection 1.3 (yellow).
• Interim O&M (Operation & Maintenance) before COD (Commercial Operation Date). Subsection 1.4 (violet).



CTV, Crew Transfer vessel
SOV, Service Operational vessel
M&E, Mechanical & Electrical
O&M, Operation & Maintenance

Figure 1. Flowchart of Installation & Commissioning of an offshore substation.

a) Subsection 1.1 **Sail away & Installation vs weather**. This methodology starts from the sail away, which is the transportation of the offshore substation from the origin port to the wind development area where the installation is taking place. The risk associated with this activity is the timing of transportation and the installation, particularly if it is programmed during summer or winter. The installation is performed by an Installation Vessel (IV), which depends on favourable weather to install the jacket and then the substation.

b) Subsection 1.2 **Mechanical and Electrical (M&E)** readiness. Ensuring mechanical and electrical completion, allowing the commissioning activities to be performed before sail-away, while the substation remains at its fabrication port. Any work that must be performed offshore after the substation has been installed at its final location requires significantly more time and effort compared to completing the same activities while the unit is still at the origin port.

In addition, offshore substations have strict limitations on the number of personnel that can be accommodated on board during their offshore phase. Typically, this limit ranges between approximately 50 and 80 personnel when a jack-up vessel is present to support substation-related activities. If no jack-up vessel is available, the number of personnel allowed on board must be further reduced.

Key factors that need to be considered for the completion of the offshore substation readiness:

- Ensure a complete factory acceptance test (FAT). Commissioning and engineering teams must actively participate in all substation tests. The most important systems to develop during the FAT and later during SAT (Site Acceptance Test) in an offshore substation are listed below in Table 1.

Table 1. System to be performed FAT.

MAIN EQUIPMENT	DIESEL GENERATOR
Shunt reactor 1	Diesel Generator 1
Main transformer 1	Diesel Control System Panel 1
Shunt reactor 2	Diesel Generator 2
Main transformer 2	Diesel Control System Panel 2
Main Auxiliary transformer 1	Diesel Transfer Pump
Main auxiliary transformer 2	Diesel Tank System
GIS- Medium Voltage	HVAC
GIS-High Voltage	HVAC Control Panels
Protection, Control & Monitoring Cabinets Medium voltage	Air Handling Unit
Protection, Control & Monitoring Cabinets High voltage	Dry Coolers
UPSs and rectifiers	Chillers
UPSs and rectifiers panels	FIRE FIGHTING
Low Voltage panels 1	Fire Alarm System
Low Voltage panels 2	Foam System
COMMUNICATION AND IT	Gas Inert system
Radio communication System	Helideck Fire Fighting
Fiber Optic Distribution system Rack / boxes	CONTROL SYSTEM
CCTV	Control System & Automation (SCADA)
Telephone System	Auxiliary Control Monitoring System
ACS (Access control system)	Fiscal Metering system

- A dedicated construction program should include the early involvement of the commissioning team to begin pre-verification activities as soon as possible. This allows potential issues or required modifications to be identified at an early stage, helping ensure a more efficient installation and commissioning process.

- Perform all site acceptance tests (SAT), which may include the high and medium voltage tests on all the equipment, before sailing away and the completion of protection, control, and monitoring test and auxiliary system tests.

c) Subsection **1.3 Energization through completion of commissioning**. Following the initial energization of the substation, the completion of most mechanical and electrical works—aside from a limited number of punch list items—marks readiness for the next phase. At this point, a decision must be made regarding the demobilization of the jack-up vessel that has been supporting the operations, as its high daily cost makes continued use inefficient for the project.
The commissioning team takes the responsibility for the remaining activities, including full energization and the required testing to confirm the substation's operational readiness. To support ongoing work offshore, appropriate logistical solutions for transporting technicians and workers need to be arranged, with transit time between the port and the substation being a key factor.

d) Subsection 1.3 **Interim O&M (Operation & Maintenance) before COD (Commercial Operation Date)**. The interim period refers to the time between the full readiness of the offshore substation and the Commercial Operation Date (COD), when the wind farm is handed over to the Operations Team and begins commercial operation with the grid operator. This phase can last from approximately three months to one year, making a well-defined logistics plan essential.

Different metrics and historical weather data can be applied to mitigate the risks.

- **Metric of the M&E completion of the offshore substation before sail away,**

The weight distribution for the seven systems previously mentioned in Table 1 are equal, and the procedure/protocols weigh is 30% while the functional test 70%.

G = General progress

P/P= procedures/protocols FT=Functional Test

T=Total Commissioning Progress

P/P= %Acepted+0.5 ·%Accepted with comments+0.6· %Under review

FT= %Completed + 0.5· % in progress

G= 30% P/P + 70% FT

T=avg ΣFT

Table 2 can be updated during the project period from time to time to make a final decision for the sail away and the constraints that can be found when installing offshore. Additionally, these metrics contribute to the visibility and effective monitoring of commissioning progress during the final offshore campaign.

Table 2. Main systems and general progress.

	PROCEDURES/PROTOCOLS			Functional Test			GENERAL PROGRESS	TOTAL COMMISSIONING PROGRESS OFFSHORE
	Accepted	Accepted with comments	Under Review	Completed	In progress	Not started	FUNCTIONAL PROGRESS	
1 Main Equipment								
2 Diesel Generator								
3 HVAC								
4 Fire Fighting								
5 Control System								
7 Communication and IT								

If the result of the Total Commissioning progress is:

- Below 60%, the offshore substation has poor termination.

- Between 60%-70%, the termination is basic.
- Between 70%-80% is acceptable.
- More than 80% is satisfactory.

  - **Metric for logistics.**

The overall project schedule—particularly offshore activities—is highly influenced by **weather downtime**, which can significantly impact construction (Installation of the offshore substation), commissioning, and O&M phases. Weather risk is typically assessed using statistical percentiles (P10, P50, P90, and P100) based on historical data. These estimates help plan activities and determine realistic timelines for completion and final handover. The percentile applied depends on the project's risk tolerance and the specific activity being scheduled.

P10: There is a 10% probability that downtime does not exceed the values provided.
P50: There is a 50% probability that downtime does not exceed the values provided.
P90: 90% probability that downtime does not exceed the values provided.

Regarding logistics, the options are CTVs, SOVs, an installation vessel (IV), a jack-up vessel, and Helicopters Eq. (1).

$$\text{Logistic (W,H)} \begin{cases} \textbf{CTV} & \text{if } W < 20 \ \land \ H_s \leq 1.5 \\ \textbf{SOV} & \text{if } W < 20 \ \land \ H_s \leq 2.2 \\ \textbf{Helicopter} & \text{if } W < 18 \\ \textbf{IV} & \text{if } W < 25 \ \land \ H_s \leq 3.0 \\ \textbf{Jack-up} & \text{if } W < 50 \ \land \ H_s \leq 5.0 \end{cases}$$

(1)
W= wind speed measured at 150 mts, close to where the nacelle and blades are located
H= height of standard waves; in case of more conservative results, H_{max} can be used.

There is also the option to integrate weather and wave percentiles, together with the specific month of execution, to assess the most suitable solution and estimate the number of workable days. This analysis consistently considers wind speed at 150 m height. Accordingly, the parameters and functions are defined as follows, Eq. (2):

$$\text{Logistic } f_p \text{ } (W_p, H_p) \begin{cases} \textbf{CTV} & \text{if } W_p < 20 \ \land \ H_p \leq 1.5 \\ \textbf{SOV} & \text{if } W_p < 20 \ \land \ H_p \leq 2.2 \\ \textbf{Helicopter} & \text{if } W_p < 18 \\ \textbf{IV} & \text{if } W_p < 25 \ \land \ H_p \leq 3.0 \\ \textbf{Jack-up} & \text{if } W_p < 50 \ \land \ H_p \leq 5.0 \end{cases}$$

(2)

$W_p(m)$= wind speed percentile *p* per month *m.*
$H_p(m)$= wave height percentile *p* per month *m.*
P= percentile $p \in \{10 \ldots 100\}$.

There are different scenarios, depending on the percentile:
F_{10} = *aggressive scenario* (10% probability that the weather and waves are favorable).
F_{50} = *mid scenario* (50% of probability).
F_{90} = *conservative scenario* (90% of probability).

A binary operability indicator can be defined for each logistic asset *i*, Eq (3):

$$O_i\,(p,m) \begin{cases} \mathbf{1} & \text{if } W_p(m) \leq W_i^{max} \land \ H_p(m) \leq H_i^{max} \\ 0 & \text{asset no applicable} \end{cases}$$

(3)
W_i^{max} and H_i^{max} are the operational limits of the logistic asset *i.*
O_i=1 indicates the logistic asset is operable.
O_i=0 indicates that the logistic asset is not operable.

Depending on the available days, the project's percentile, and the termination percentage for the offshore substation, a different type of logistics should be chosen.

3. Case Study

Regarding the case study, although the methodology can be applied to a generic offshore wind farm, the study is focused on experience within the United States of America, where this type of industry is affected by several aspects:

- as the existing strong Union Force workers, political instability
- and a special relevant regulation that affects the offshore wind industry, such as the Jones Act[9], also known as the Merchant Marine Act of 1920, which requires that ships transporting cargo between USA ports must be owned, built, crewed, and documented by USA nationality.
- In addition to state agencies, two key federal agencies regulate permitting and oversee offshore project development, and are critical for the project in case the Presidential Administration is not in favour of this projects or there are any incident that these agencies re-consider the continuity of the project: the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE). BOEM is responsible for resource management, including leasing and permitting, while BSEE focuses on safety and environmental oversight.

The offshore wind projects developed in the United States are limited as the industry is under development; however, several examples can be identified, such as those located off the coast of Massachusetts, for example, the Revolution project [10], which has been approved for the Construction and Operations Plan (COP).

Ensuring mechanical and electrical readiness before sail-away is critical for later offshore activities. In locations such as the Massachusetts coast, productivity may be affected by limited offshore experience among union workers. Therefore, completing as much commissioning and related work as possible at the fabrication port can significantly reduce offshore time, manpower requirements, and installation complexity.

4. Results and discussion

The findings of the methodology give us a good result in mitigating the risk, a better understanding of the importance of improvements during critical activities, and the different options to discuss.
The data on the status of the M&E completion of this paper has been collected from the actual projects that are developed in the area of the Coast of Massachusetts and projects such as the Revolution, which is under construction, in Table 3.

Table 3. Results of the main systems and general progress.

OFFSHORE SUBSTATION	PROCEDURES/PROTOCOLS			Functional Test			GENERAL PROGRESS	TOTAL COMMISSIONING PROGRESS OFFSHORE
	Accepted	Accepted with comments	Under Review	Completed	In progress	Not started	FUNCTIONAL PROGRESS	
1 Main Equipment	98%	1%	1%	95%	5%	0%	98%	92%
2 Diesel Generator	99%	0%	1%	99%	0%	0%	99%	
3 HVAC	95%	3%	2%	75%	10%	15%	85%	
4 Fire Fighting	100%	0%	0%	95%	5%	0%	98%	
5 Control System	80%	12%	8%	70%	10%	20%	80%	
7 Communication and IT	85%	10%	5%	92%	4%	4%	94%	

A result of 92% indicates that the offshore substation termination is in a very advanced state, and consequently, commissioning is progressing at a high level.

The next step to consider is the logistics and time period to apply for the different subsections, taking into consideration the metrics indicated before for the Crew Transfer Vessels (CTVs), Service Operation Vessel (SOV), Installation vessel, Jack-up Vessel, and Helicopter.

Logistics: considering the different weather results, determine whether to use different logistics.

Considering the hindcast information from the National Data Buoy Center[5] and some relevant papers [6], [7], [8] , where it can see data historically. It can simulate ocean behavior and determine the workable days in different months.

From the data obtained, the metrics can be applied to different logistics.

In Table 4, we can see the days available to work with a CTV during the different months.

Table 4. Result of the days available to work with CTV.

Days per month when weather requirements are met										
		Weather percentile from hindcast								
Month	Total	P10	P20	P30	P40	P50	P60	P70	P80	P90
Jan	31	15	13	12	11	11	10	10	9	8
Feb	28	14	12	11	11	10	10	10	9	7
Mar	31	15	15	14	13	13	12	11	10	10
Apr	30	19	18	16	15	15	14	12	11	9
May	31	22	21	19	19	18	17	16	15	12
Jun	30	23	22	21	20	19	18	17	16	16
Jul	31	27	26	25	24	23	23	22	21	19
Aug	31	28	27	26	26	25	24	24	23	22
Sep	30	24	23	22	21	21	19	19	18	15
Oct	31	21	20	19	18	17	17	16	15	14
Nov	30	16	16	14	13	13	12	12	11	10
Dec	31	14	14	14	13	12	11	10	9	8

In Table 5, we can see the days available to work with an SOV during the different months.

Table 5. Result of the days available to work with SOV.

Days per month when weather requirements are met										
		Weather percentile from hindcast dataset								
Month	Total days	P10	P20	P30	P40	P50	P60	P70	P80	P90
Jan	31	27	26	26	26	25	24	24	23	22
Feb	28	25	25	24	24	23	23	22	21	21
Mar	31	29	28	28	27	26	25	25	24	24
Apr	30	30	29	29	28	28	28	27	26	24
May	31	31	31	31	31	30	30	30	29	29
Jun	30	30	30	30	30	30	30	30	30	29
Jul	31	31	31	31	31	31	31	31	30	30
Aug	31	31	31	31	31	31	31	30	30	29
Sep	30	30	30	29	29	29	29	28	27	27
Oct	31	31	30	29	29	28	28	27	26	26
Nov	30	28	28	27	26	26	25	25	24	23
Dec	31	28	27	26	26	25	24	24	23	20

In Table 6, we can see the days available to work for an installation vessel. Which will be used for the installation of the offshore substation.

Table 6. Result of the days available to work with an installation Vessel.

Days per month when weather requirements are met										
		Weather percentile from hindcast dataset								
Month	Total days	P10	P20	P30	P40	P50	P60	P70	P80	P90
Jan	31	24	20	15	14	12	11	10	9	7
Feb	28	20	16	14	13	12	10	9	9	7
Mar	31	25	22	20	17	16	15	14	11	11
Apr	30	27	25	23	22	19	17	16	14	12
May	31	30	29	27	26	24	23	22	21	16
Jun	30	29	28	28	27	26	25	23	22	18
Jul	31	31	30	30	29	28	28	27	25	19
Aug	31	30	30	29	28	28	27	26	24	15
Sep	30	27	26	25	24	23	21	19	17	10
Oct	31	27	25	23	21	20	18	17	14	12
Nov	30	24	22	19	18	16	15	13	10	9
Dec	31	25	21	18	15	14	12	11	10	7

In Table 7, we can see the days available to work for a helicopter.

Table 7. Result of the days available to work with SOV.

Days per month when weather requirements are met										
		Weather percentile from hindcast dataset								
Month	Total days	P10	P20	P30	P40	P50	P60	P70	P80	P90
Jan	31	0	0	0	0	0	0	0	0	0
Feb	28	0	0	0	0	0	0	0	0	0
Mar	31	3	2	2	1	1	1	1	1	0
Apr	30	10	9	8	7	7	6	6	5	5
May	31	11	11	9	9	8	7	7	6	5
Jun	30	12	12	10	9	9	9	7	7	7
Jul	31	14	13	12	12	11	11	10	9	9
Aug	31	14	14	13	13	13	12	11	11	10
Sep	30	5	4	4	4	4	3	3	3	3
Oct	31	0	0	0	0	0	0	0	0	0
Nov	30	0	0	0	0	0	0	0	0	0
Dec	31	0	0	0	0	0	0	0	0	0

The results for the jack-up vessel are not relevant to developing an equivalent table, as the workability days per year are almost for the full year.

The results obtained enable a project to determine the most appropriate solution within the required activities timeline.

The sail-away and offshore installation. Table 6 provides accurate information to make the best decision for the project.

The results presented in Table 3 for **mechanical and electrical readiness** indicate a satisfactory percentage of completion achieved, thereby reducing the scope of work remaining to be executed offshore.

Tables 4, 5, and 7 results allow for selecting the best solution for the best period and activity.

5. Conclusions

This paper presents a novel methodology that identifies the key risks commonly encountered during the most critical phases of offshore substation and the importance of this in an area such as the Coast of Massachusetts.

With Crew Transfer Vessels (CTV), which are commonly used for **interim maintenance**. However, SOVs are generally preferred for the period of **Energization through completion of commissioning** as they reduce transit time and are less affected by harsh weather conditions compared to CTVs.

Accordingly, January corresponds to the most restrictive month for CTV operations (P90), whereas August represents the most favourable conditions (P10). The percentile ultimately adopted is determined by the project, depending on the scheduling strategy considered most advantageous.

In the event of a substation trip during a storm, the most effective solution is an offshore substation equipped with a helideck and supported by a contracted **helicopter service**. This allows technicians to quickly access the site and restore power. If a helideck is not available, access must be performed by hoists; additional safety procedures are required.

During a blackout, rapid access to the substation is critical to protect wind turbines as they need a power supply to be in safe mode. Although helicopter support increases project costs, it can significantly reduce production losses and the risk of turbine damage. As a cost-effective approach, developers may share emergency helicopter services to ensure reliable offshore access while limiting expenses.

Acknowledgement

This work was supported by the URBISOS project (CIGE/2024/193) funded by the Generalitat Valenciana and by Ayuda a Primeros Proyectos de Investigación (PAID-06-24) funded by Vicerrectorado de Investigación de la Universitat Politècnica de València.

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