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# Transport Cost Optimization of Offshore Wind Turbine Installation on The Indonesia Sea

## Transportkostenoptimierung der Offshore-Windturbineninstallation auf dem indonesischen Meer

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**Since wind turbine is located offshore, transportation and installation of an offshore wind turbine have high capital costs. The method of pre-assembly is used to optimize the use of the transportation vessel that is chartered to transport and install the wind turbine on an offshore remote location. Until this study is conducted, there is no offshore wind farm in Indonesia. This study uses the methodology of annual average wind velocity and bathymetry data to determine a possible location for an offshore wind farm on the Indonesian sea. The total duration of transportation and installation of wind turbines to construct a wind farm in Indonesia is calculated using scenarios of different pre-assembly methods and transportation vessels. By doing a comparison of different scenarios, the optimal combination of total duration and costs can be seen. The determined transportation vessel on this thesis is a jack up barge and Self-Propelled Installation Vessel (SPIV). The least time spent to construct a wind farm on the Indonesian sea of both transportation vessels is by using the pre-assembly of the "*Bunny-Ear*" method with the wind turbine tower in one piece and the remaining blade. It can be concluded that to optimize the transport cost of offshore wind farm installation on Indonesian sea is by using the combination of said pre-assembly method and by using jack up barge with the total duration of wind turbine transport and installation of 34 Days. 6 Days longer than the other scenarios of using SPIV with the same pre-assembly method.**

*[Keywords: Indonesian Sea, Offshore, Self-Propelled Installation Vessel, Transport Cost Optimization, Wind Turbine]*

**Da sich die Windkraftanlage auf hoher See befindet, sind Transport und Installation einer Offshore-Windkraftanlage mit hohen Investitionskosten verbunden. Die Methode der Vormontage wird verwendet, um die Nutzung des Transportschiffs zu optimieren, das für den Transport und die Installation der Windturbine an einem abgelegenen Offshore-Standort gechartert wird. Bis zur Durchführung dieser Studie gibt es keinen Offshore-Windpark in Indonesien. Diese Studie verwendet die Methodik der jährlichen durchschnittlichen Windgeschwindigkeit und der bathymetrischen Daten, um einen möglichen Standort für einen Offshore-Windpark auf dem indonesischen Meer zu bestimmen. Die Gesamtdauer des Transports und der Installation von Windturbinen zur Errichtung eines Windparks in Indonesien wird anhand von Szenarien mit verschiedenen Vormontagemethoden und Transportschiffen berechnet. Durch den Vergleich verschiedener Szenarien kann die optimale Kombination aus Gesamtdauer und Kosten ermittelt werden. Das in dieser Arbeit ermittelte Transportschiff ist ein Hubschiff und ein Self-Propelled Installation Vessel (SPIV). Der geringste Zeitaufwand für die Errichtung eines Windparks auf dem indonesischen Meer wird bei beiden Transportschiffen durch die Vormontage der "Bunny-Ear"-Methode mit dem Windturbinenturm in einem Stück und dem verbleibenden Blatt erreicht. Es kann geschlussfolgert werden, dass die Optimierung der Transportkosten für die Installation eines Offshore-Windparks auf dem indonesischen Meer durch die Kombination der besagten Vormontagemethode und der Verwendung eines Hubkahns mit einer Gesamtdauer des Transports und der Installation der Windturbine von 34 Tagen erfolgt. Dies ist 6 Tage länger als die anderen Szenarien der Verwendung von SPIV mit derselben Vormontagemethode.**

*[Schlüsselwörter: Indonesisches Meer, Offshore, Selbstfahrendes Installationsschiff, Transportkostenoptimierung, Windkraftanlage]*

## 1 INTRODUCTION

The world has begun to slowly convert to electricity generation from renewable energy. One of the effective methods is by using a wind turbine to harvest wind energy.

A group of the wind turbine in a specified area is called a wind farm. Most of the available wind farms in the world are onshore wind farms. But these days, wind energy industries are facing a problem of rejection from the community when constructing an onshore wind farm. The reason is that the large dimension of the wind turbine pollutes the area visually. Thus, more wind energy industries are constructing these wind farms offshore.

There are upsides to constructing an offshore wind farm. Besides eliminating the visual pollution onshore, the wind turbine used on an offshore wind farm is bigger. Having bigger wind turbines leads to more electricity generated by the wind farms. Besides, there are fewer obstructions for the wind turbine to harvest wind energy when constructing offshore wind farms. With that said, there are downsides to constructing offshore wind farms. The main problem is the high capital cost for the transportation and installation (T&I) of the wind turbine compared to onshore wind farms.

Because the construction is offshore, the T&I of the wind turbines is dependent on the weather. According to a study from [SF14], modified from the cost on Offshore Wind Energy Cost Modelling by [KS12], the installation cost for a wind turbine on a wind farm can reach as high as $152 Million. Moreover, this paper will focus on the installation of the offshore wind farm on the Indonesian sea as a case study. The Indonesian government has set a goal of having 23% of the national electricity generation from a renewable resource by 2025 [Dir20]. But currently, there is no offshore wind turbine available on the Indonesian sea. Thus, the author must first determine a suitable location for the offshore wind turbine by using several methodologies.

This paper discusses further the optimization of the vessel to load the wind turbines using the means of comparison of scenarios of using different wind turbine pre-assembly methods and types of transportation vessel. Then the total duration of the turbine installation is calculated by using the travel time calculation from [SF14] with modification to the equation based on several assumptions to ease the calculation. All scenarios and calculations will be applied to the Indonesian sea.

## 2 LITERATURE REVIEW

### 2.1 TRANSPORTATION VESSEL FOR OFFSHORE WIND TURBINE INSTALLATION

Choosing the transportation vessel for the installation of an offshore wind turbine requires several capabilities. The general capabilities of a turbine transport vessel are a capable loading deck and the various transit speed of the vessel. The loading deck determines the number of loaded wind turbines on each transport vessel trip. While the transit speed determines greatly the duration of the transport vessel to cover up the distance between the port and the offshore site. Other than the general capabilities, these transport vessels must have a capable loading crane and jack up capabilities. The loading crane is to load the pre-assembled wind turbine on the port and install the wind turbine on the offshore site. While the jack up capabilities of a vessel are required so the transport vessel can install the offshore wind turbine steadily [KS12].

Because the crane will lift the pre-assembled wind turbine, the loading crane must have a lifting capacity greater than the wind turbine itself. Other than that, the lifting crane must be capable of lifting the wind turbine as high as the hub height of the wind turbine. The crane capacity can be determined when the technical data regarding the wind turbine which will be used is determined [Her02].

The choice for jack up capabilities of a transport vessel is dependent on the depth and the wave height of the offshore installation site. Since the data regarding the wave height of the offshore site and the jack up capabilities of a transport vessel is not publicly available, this paper will assume that the chosen transport vessel has fulfilled the requirements to install the wind turbine on the chosen offshore site. The method of cost for the transport vessel is chartered daily. Thus, determining the total duration of the wind turbine installation is crucial, to further determine how long the transport vessel should be chartered. The cost of the charter depends on the capabilities of the transportation vessel itself. The more capable a transport vessel on loading wind turbines, the greater the daily charter cost. Below are the available types of transport vessels for the T&I of offshore wind farms [Cof20], [KS12]:

a) Lift-Boats

Lift-boats are self-propelled, relatively smaller than other transportation vessels, have usually 3 jacking up legs, and a shorter boom crane. The size of a lift-boat is ranging from small to a larger size lift-boat. Smaller lift-boats have a load capacity of 75 Tons and crane capacity of 50 Tons, while bigger lift-boats have a load capacity of 750 Tons and crane capacity of 500 Tons. Transporting a wind turbine is possible for a large lift-boat, around 2 turbines on each sail. Smaller lift-boat is not capable of transporting and installing a wind turbine.

b) Jack up Barges

Jack up barges size is relatively smaller than SPIV and bigger than lift-boats. Typical jack up barges have 4 jack-up legs and are not self-propelled. Jack up barges needs another vessel for towing it to the installation site. The towing speed depends on the tug power and usually ranges from 4 to 8 knots. A large jack up barge might carry 6 to 8 wind turbines, whilst smaller jack up barges can carry up to 2 wind turbines. One example of the capacity of the jack up barge is *JB – 115* has a load capacity of 1,250 Tons and a crane capacity of 300 Tons. This is considered to be a smaller size jack up barge, which has a loading area of 1,000 $m^2$.

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c) Self-Propelled Installation Vessel (SPIV)

SPIV is also referred to as Wind Turbine Installation Vessels (WTIV) because of its use almost exclusively for wind turbine installation. The difference from lift-boats is SPIV is bigger and from jack up, barges are the self-propelled characteristic of SPIV. Relatively, SPIV is bigger than lift-boats and jack up barges, but smaller compared to heavy-lift vessels. SPIV has usually 6 to 8 jack-up legs (depending on its size), travels at 8 to 12 knots, and has variable deck loads up to 12,000 Tons (*Pacific Orca*). The number of wind turbines transported depends on the loading area of the SPIV, for example, *Pacific Orca* can transport up to 12 wind turbines with rated energy of 3.6 MW of each turbine [Shi20].

d) Heavy-Lifts Vessel

Heavy-lifts vessels are widely used for offshore oil and gas construction. The uses of this vessel for wind turbine installation are seldom. But for the installation of the foundation work, offshore wind turbine substation, or even installing a whole pre-assembled wind turbine is possible. This vessel travels at 8 to 12 knots.

The cost for these transportation vessels is not available publicly. But SPIV and Heavy-lift vessels are more expensive than the other types of transportation vessels for their capabilities of having to carry more wind turbines and self-propulsion characteristics. Quoted from [Tho14] the charter cost of a SPIV can reach up to €125,000 daily and Jack up barge can reach up to €80,000 daily.

### 2.2 Pre-Assembly Configurations

Since the offshore installation of the wind turbines is in a harsh condition, it is a trend for the offshore wind industries to have a pre-assembly method of the wind turbine. One of the main reasons is to have fewer lifting numbers on the offshore installation site. Having fewer lifting numbers means having faster installation time, besides the pre-assembly of the wind turbine is done on the port. Weather does not have a direct impact on the pre-assembly of the wind turbine. The transport vessel must load the pre-assembled wind turbine on port and install the pre-assemble turbine on the offshore installation site. There are currently 6 configuration methods of offshore wind turbine pre-assembly [Ura11]. The configuration methods are as follow:

a) Configuration 1: Nacelle and Hub, Separated Tower, and 3 Blades

The first configuration is the pre-assembly of the nacelle and hub onshore. The tower is separated into two pieces. The blades require a stacker to be transported. There are in total of 6 separate pieces that are transporting from onshore to the installation area.

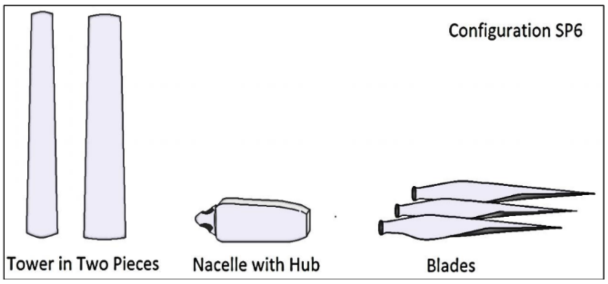


*Figure 1. Illustration of the 1st Configuration Method*

b) Configuration 2: Tower in one piece, Nacelle and Hub, 3 Blades

The difference from the first configuration is the unseparated tower. Nacelle, hub, and blades have the same configuration. By this configuration method, it decreases the number of lifting compared to the first configuration. 5 parts in total must be transported.

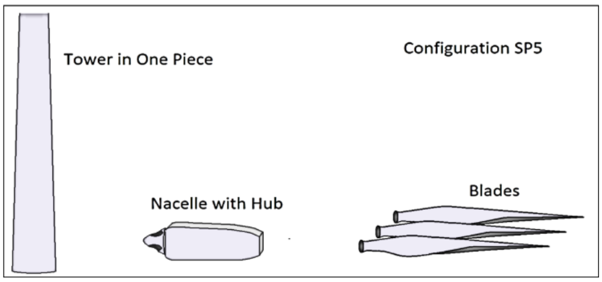


*Figure 2. Illustration of the 2nd Configuration Method*

c) Configuration 3: Hub and 3 Blades, Separated Tower, Nacelle

The pre-assemble method of this configuration lies on the rotor. The rotor is when the 3 blades and the hub is joined together. The tower is separated into a two-piece and the nacelle is transported by itself. Since the blades are pre-assembled, there is no need to lift the blades individually on the installation site. That means there is less lifting on-site that must be done compared to the previous configuration. In total there are 4 liftings needed, two from the tower, the nacelle, and lastly the pre-assembled rotor.

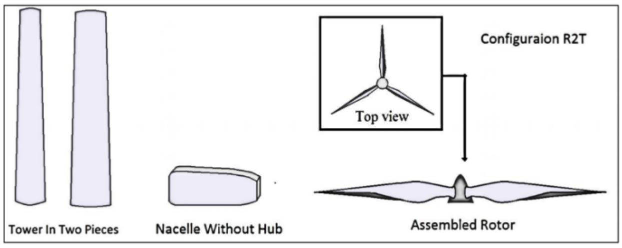


*Figure 3. Illustration of the 3rd Configuration Method*

4) Configuration 4: Nacelle, 2 Blades, and Hub (*Bunny Ear*), Separated Tower, 1 Blade

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The fourth configuration is widely used in the transportation of offshore wind turbine installation. This configuration uses the so-called bunny ear pre-assembly method. It is the pre-assembly of the nacelle, hub, and 2 of the wind turbines blades. The other turbine parts of this configuration consist of a separated tower, and the remaining blade. When loading the wind turbine to the transport vessel, the nacelle that has connected to the hub and 2 blades can be directly laid on the deck. This configuration method also takes 4 lifts for loading and installation, one lift from the bunny ear, two from the tower, and the remaining blade.

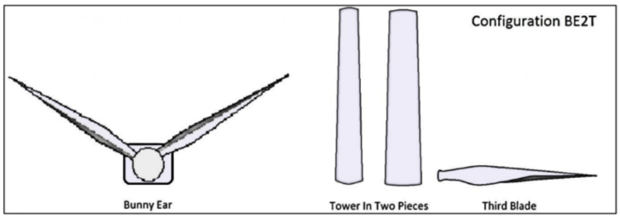


*Figure 4. Illustration of the 4th Configuration Method*

e) Configuration 5: Nacelle, 2 Blades, and Hub (*Bunny Ear*), Tower in one piece, 1 Blade

The difference compared to the previous configuration lies in the loading of the unseparated tower. This further decreases the needed loading area and number of lifts to 3. The only thing to consider in the fifth configuration method is the lift capacity of the crane because the crane should be able to lift the whole tower of the turbine.

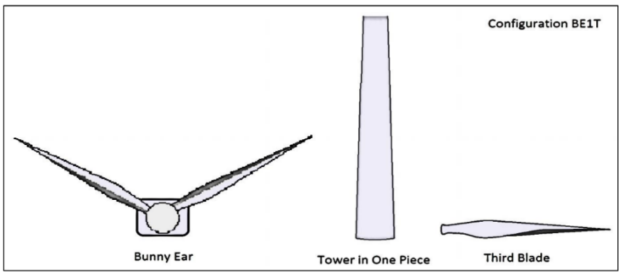


*Figure 5. Illustration of the 5th Configuration Method*

f) Configuration 6: The Whole Turbine

The tower, nacelle, and rotor are all pre-assembled onshore and transported to the offshore installations area. This configuration method requires a heavy-lift vessel and a crane that has a great deal of lift capacity. Even for a 6 MW wind turbine, a crane lift capacity of 500 Ton is needed. The greater the energy generated, means the larger the wind turbine dimension. Thus, a better lift capacity for the crane is needed. Moreover, the maximum lifting height of the said crane should be able to reach the hub height under heavy load. If an offshore wind project has a suitable transportation vessel and crane for this configuration, the installation time would be much quicker since only requires 1 lift of the crane.

The determination of the configuration is important to the calculation of the total duration of offshore wind turbine installation. In a sense that different configuration methods differ on the loading area on the transport vessel needed and the lifting number of each configuration.

## 3 METHODOLOGY

The methodology used in this paper is mainly to determine the offshore wind site in Indonesia. Followed by the equation used to determine the total duration of a wind turbine T&I on Indonesian seas, with the determination of several variables and assumptions to complete the equation.

### 3.1 OFFSHORE WIND FARM SITE DETERMINATION

To determine the offshore wind farm site on the Indonesian sea, this paper will use the method of Annual Average Wind Velocity Data and Bathymetry Data [Win17]. To build a functioning wind farm on the Indonesian sea, more concrete data should be gathered on the site to make certain that a wind farm is possible to be constructed on the chosen site. Additional data such as the wave height on the chosen site, seabed characteristics, and other supporting data must be researched.

Based on the [Wik20], wind turbines are divided into classes regarding their Annual Average Wind Speed. The minimum Average Annual Wind Speed of a wind turbine at hub height is 6 m/s and a maximum of 10 m/s. Looking at the Annual Average Wind Speed of Indonesia from the year 2004 – 2015 data can be shown that only a small part of Indonesian seas is qualified for IEC 61400 regulation of wind turbine. Although the qualified area is scarce, the potential of this area can be developed. To further assure that the chosen site is suitable for the construction of an offshore wind farm, information about the sea depth of the site is provided using Bathymetry Data.

The seabed depth correlates directly to the choice of the offshore wind turbine foundation. The offshore site determination on this paper will only concern whether or not the seabed depth of the determined offshore site is currently in the range of the current capabilities of the offshore wind turbine foundation technology. Currently, using a tripod foundation can reach a seabed depth of 50 m. With higher trends of offshore wind turbine these days, more foundation is being developed to be able to reach a seabed depth of more than 50 m. Thus, the determined maximum seabed depth for the offshore wind farm site determination on this paper is 80 m.

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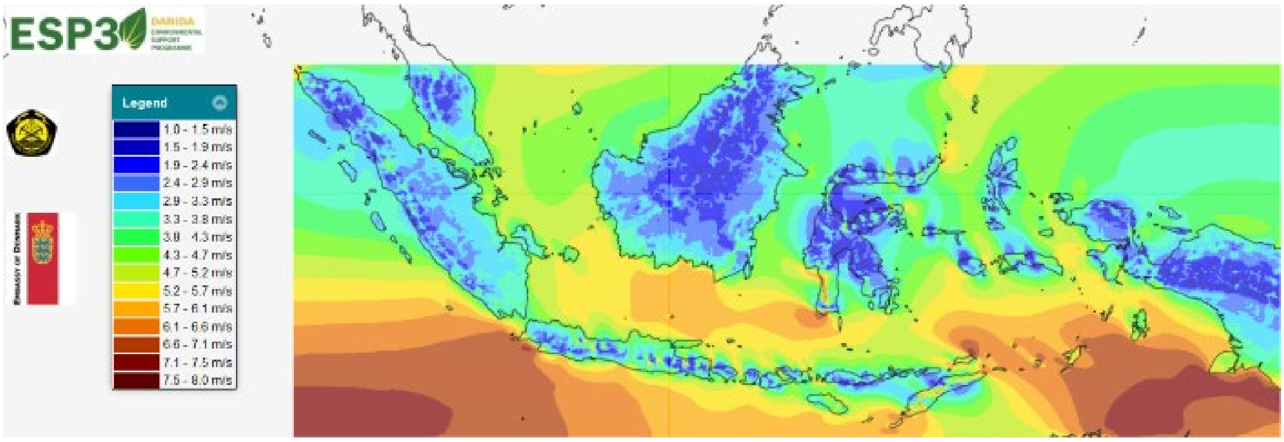


*Figure 6. Average Annual Wind Velocity of Indonesia from 2004 – 2015*

### 3.2 Travel Time Function

The calculation of the total duration of offshore wind turbine installation on the Indonesian sea in this paper uses the equation from [SF14]. The equation is stated as below:

$$T_v = \frac{N_i\,A_j}{V_N\,V_S\,A}(2D) + \left[\frac{\left(N_i - \frac{N_i\,A_j}{V_N\,A}\right)d}{V_S}\right] + \left(N_i\,t_{FS} + \frac{N_i\,A_j}{V_N\,A}\,t_{PL}\right) \quad (1)$$

Where:
Indices:
$i$ = Index for types of turbine class used
$j$ = Index for types of turbine pre-assembly used
Variables:
$N_i$ = Number of turbines in the farm [unit]
$A_j$ = Area required for one turbine during transport [m$^2$]
$A$ = Deck area available for transporting foundation [m$^2$]
$V_N$ = Number of vessels used [unit]
$V_S$ = Vessel transit speed [m/s]
$D$ = Distance from port to site [m]
$d$ = Distance between two turbines site [m]
$t_{PL}$ = Pre-loading time at the port [h]
$t_{FS}$ = Pre-loading time at turbine site [h]

The equation is an addition of Back-and-Forth Trip, Total Travel Distance within the Wind Farm, and Pre-loading time calculation, correspond to the order of the equation from left to right. On the sub-chapter of variables determination and assumptions, the pre-loading time calculation will be altered to the installation time of the wind turbine to deduce the total offshore wind turbine T&I duration calculation.

### 3.3 Variable Determination and Assumptions

To reach the objective of calculating the total T&I of an offshore wind turbine on the Indonesian sea, several variables must be first determined. The variables that are determined and assumed would be dependent on the project itself. Meaning the number can be further altered to suit the project requirements. For example, the total power generated determined in this study can be altered to the requirement on the real project. The assumption made in this paper is based on the observation of previous offshore wind farm construction projects, which is stated in past studies and literature.

#### 3.3.1 Variable Determination

From the travel time formula stated above, several variables must be determined. Such as the types of the wind turbine to determine the turbine rotor diameter, and the number of wind turbines ($N_i$). Besides, the type of vessels is determined to see the available loading deck area ($A$) and the vessel transit speed ($V_S$). The last number of vessels used ($V_N$) is determined.

a) Type of wind turbine

The type of wind turbine that is determined in this study is a wind turbine with 3 MW power generated with a low wind class at 6 m/s average velocities at hub height. One suitable wind turbine for the specification is by using *Vestas V90*-3. The variable dependent on this wind turbine determination is the rotor diameter of approximately 90 m [KS12]. The rotor diameter is used for the calculation of the distance between two turbines at the installation site ($d$) which is approximately 10 to 15 times the rotor diameter ($d \approx 10 \times blade\ diameter$). This number of turbines spacing is to minimize the aerodynamic losses between turbines under prevailing wind conditions.

b) Number of wind turbines ($N_i$)

The number of wind turbines on the wind farm determined by the author is 30 Turbines. Yielding a total of $N_i \times wind\ turbine\ power\ generated = 90\ MW$ power generated from the wind farm.

c) Types of Vessels

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This paper will determine 2 different types of vessels, Jack up Barge and SPIV. The Jack up Barge would be *Neptune* and the SPIV would be *Sea Challenger*. The technical data needed for the calculation is the loading deck area $(A)$ and vessel transit speed $(V_S)$. One of the factors of the optimization of transportation and installation of the offshore wind farm on the Indonesian sea would be to compare the calculation for a different types of vessels. Hence, 2 different types of vessels are determined for the calculation in the next chapter.

d) Number of Vessels used $(V_N)$

This paper will only consider 1 vessel used for the whole offshore wind farm project.

### 3.3.2 ASSUMPTIONS

Assumptions made for this study are divided into 2 categories, general and technical assumptions. Both assumptions apply to all the calculation cases. These conditions are as follows:

- All the vessels for a different types of configurations are identical.
- All the determined turbines are identical.
- Vessels are available throughout the transportation and installation period.
- Weight concentration on the deck and crane lifting does not exceed the limit.
- The crane on the vessel is the only available crane whilst loading the turbine.
- Benign weather for the transportation and installation.

Technical assumptions will be made for some of the variables that are stated on the travel time formula. These technical assumptions are taken from the observation of previous wind farm projects and stated in the previous studies that are mentioned before.

a) Occupied deck space of 1 turbine of the different configuration method

These numbers are taken from [Ura11] based on observation and calculation. The average power generated by the turbine is 3 MW.

*Table 1. The assumption for the occupied deck space for different configuration*

| Configuration | $A_j[m^2]$ |
|---|---|
| 1 | 491 |
| 2 | 353 |
| 3 | 369 |
| 4 | 648 |
| 5 | 510 |
| 6 | - |

b) Pre-loading time at the Port $(t_{PL})$ and the Site $(t_{FS})$

On the study of [Ura11], the loading time at the port and installation at the site is approximated to 3 hours of each lift. To simplify the calculation, the pre-loading time is also included in this approximation. Because each configuration has a different number of lifts, the installation and loading time for different configurations varies. Therefore, the 3 hours assumption should be multiplied by the Number of Lifts $(N_L)$. The number of lifts of each configuration will be summarized in the next chapter.

The loading and installation of the wind turbine use the same configuration. The only difference is jacking up on the port for loading the wind turbines requires only 1 jack-up procedure (jacking down and up). While on the site, the jack-up procedure is needed for each of the wind turbines installed. Each jack-up procedure will be assumed to be 1 hour. For the assumption of total duration at the installation site, the Number of Lifts should be multiplied by the 3 hours assumption and added 1 hour for the jack-up procedure. Then to see the total duration, it must be multiplied again by the Number of Wind Turbines installed.

For the assumption of total duration at the port, each trip must be multiplied by 1 hour for the jack-up procedure. Since the vessel must be loaded with the turbine, the same method applies of multiplying the 3 hours assumption by the number of each lift. To accommodate these assumptions, a new equation to alter the pre-loading time part of the equation are as follow:

$$\left(N_i((N_L \times 3) + 1) + N_i\left(\frac{A_j}{V_N\,A} \times 1 + (N_L \times 3)\right)\right) \qquad (2)$$

After this alteration of the formula, the travel time formula is modified into the total duration of T&I of an offshore wind turbine on a wind farm project.

$$T_v = \frac{N_i\,A_j}{V_N\,V_S\,A}(2D) + \left[\frac{\left(N_i - \frac{N_i\,A_j}{V_N\,A}\right)d}{V_S}\right] + N_i\left(((N_L \times 3) + 1) + \left(\frac{A_j}{V_N\,A} \times 1 + (N_L \times 3)\right)\right) \qquad (3)$$

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## 4 Result and Analysis

This chapter will focus on determining the offshore wind farm site on the Indonesian sea based on the methodology stated in chapter 3. Besides, the technical specification of the determined wind turbine and transportation vessel will be presented. Afterward, the calculation of the total duration of transportation and installation of an offshore wind turbine will be presented in different scenarios. This chapter is ended with the analysis of the calculated data and the optimal combination in terms of duration and cost.

### 4.1 Offshore Wind Farm Location Determination

The location of the offshore wind farm will be determined with the methodology of the previous chapter. The offshore installation site will be determined based on the annual average wind velocity map data and the minimum annual average wind velocity of 6 m/s [Wik20]. Then, the location chosen by the Author will be cross-referenced with the Bathymetry data to accommodate the depth capability of the current foundation technology.

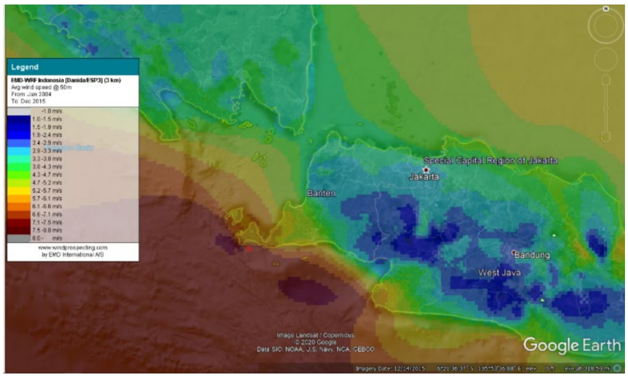


*Figure 7. Chosen Offshore Wind Farm Location.*

Figure 7 is the super-imposed map of Indonesian annual average wind velocity data in the previous chapter with the Google Earth computer program. The location determined is the bay underneath Ujung Kulon National Park. Based on the data of Wind Prospecting, the annual average wind velocity data is around 6.6 – 7.1 m/s. Just above the minimum requirement of [Wik20].

Besides the wind requirement, the depth of the chosen location is included. Figure 8 shows the Bathymetry data of the chosen location of the offshore wind farm. It can be seen on the figure that the deepest of the chosen location is 321 ft ~ 98 m and the shallowest is 0 ft ~ 0 m.

The data shown here are the rough estimation of the annual average wind velocity and the depth of the sea, by using the Google Earth computer program. This data can be used to determine the distance of the offshore wind site to the port. Which, the calculation of this paper is based on. Afterward, the optimal combination of transport cost can be deduced from the starting point (chosen port) and the offshore wind farm site.

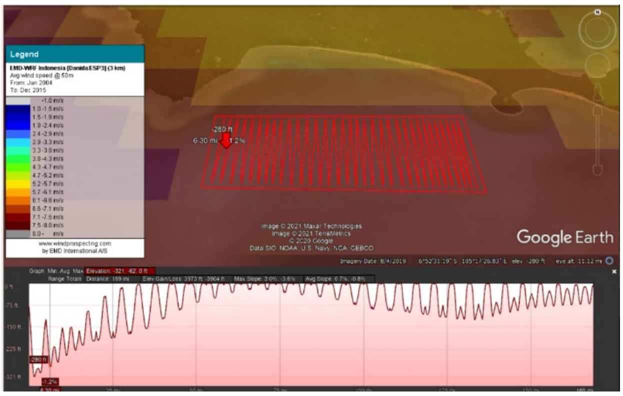


*Figure 8. Elevation Profile (Bathymetry data) of the Chosen Location [Win17]*

### 4.2 Port Determination for Starting Point

The port chosen as the starting point is the nearest container port to the offshore site. The chosen port for this paper is the Container Terminal of Merak, located in Cilegon City. There is no other possible container port in the vicinity that has the capabilities to pre-assemble and store offshore wind turbine parts.


*Figure 9. Circle: Container Terminal Location. Rectangle: Offshore Site Location*

### 4.3 Determined Wind Turbine Technical Specification

The determining wind turbine in the previous chapter is *Vestas V90-3*. Each wind turbine can generate 3 MW with a low wind class. *Vestas V90-3* is used on the *Kentish Flats* offshore wind farm project, completed in 2005. The technical specification of *Vestas V90-3* is stated below [KS12].

*Table 2. Technical Specification of Vestas V90-3*

| Technical Specification of *Vestas V90-3* | |
|---|---|
| Capacity | : 3 MW |
| Tower Height | : 62 m |
| Tower Weight | : 108 ton |
| Blade Diameter | : 90 m |
| Rotor Weight | : 42 ton |
| Nacelle Weight | : 70 ton |

The data is to complete the equation for variable $d$, the distance between 2 turbines. Variable $d$ has also been

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determined with $d = 10 \times blade\ diameter$. Besides, tower, nacelle, and rotor weight are needed for the determination of a capable transportation vessel. The weight capabilities of the loading area and lifting crane of the transport vessel must exceed the weight data in *Table 2*.

### 4.4 Determined Transportation Vessel Technical Specification

There are 2 types of vessels used in this paper. The goal is to compare each vessel along with the pre-assemble configuration to the optimal combination. The determined types of vessels are Jack up barge and SPIV. The chosen vessel for jack up barge is *Neptune* and for SPIV is *Sea Challenger*. Table 3 is the summary of both transport vessel technical specifications [Cof20].

*Table 3. Technical Specification of Chosen Transport Vessel*

| Technical Specification of Transport Vessel | | |
|---|---|---|
| | Neptune | Sea Challenger |
| Type of Vessel | Jack up Barge | SPIV |
| Loading Area (A) [m2] | 1600 | 3350 |
| Crane Capacity [Ton] | 600 | 900 |
| Transit Speed (Vs) [Knot] | 7 | 12 |
| Jacking-up Speed [m/min] | 0.7 | 0.4 |

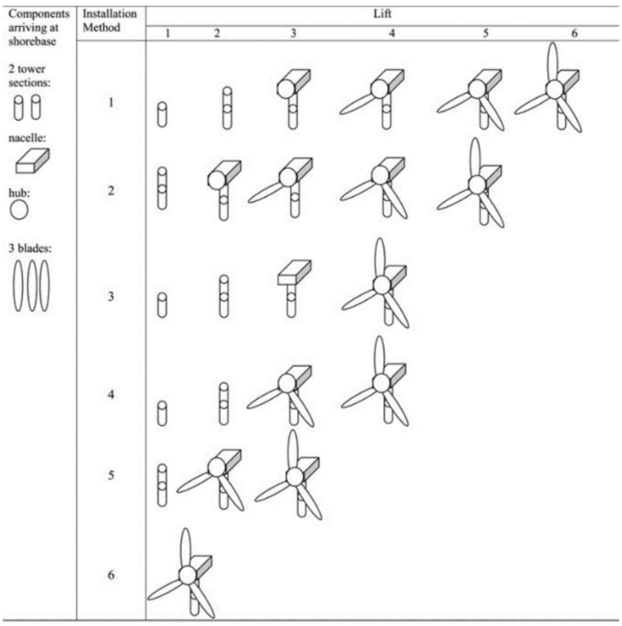


*Figure 10. Number of Lifts and Lifting Order of Offshore Wind Turbine Installation*

The data used for the calculation of the total transport duration is only the Loading Area ($A$) and Transit Speed ($Vs$). The Crane Capacity data is not used in the calculation, but to make sure that the turbine's total weight does not exceed the crane lifting capacity. Other than that, the Jacking-up Speed is useful to calculate the installation time of each turbine. But in this paper, the installation time of the turbine has been assumed in the previous chapter.

### 4.5 Number of Lifts

This sub-chapter will summarize the Number of Lifts for each different pre-assembly configuration along with its order of lifts. Figure 10 is taken from [KS12], showing the number and order of lifts for each pre-assembly configuration.

### 4.6 Calculation Scheme

The calculation scheme for the total duration of offshore wind turbine transportation and installation will starts from the determination of the transport vessel travel route, calculation of the duration per scenario, having the result of the total cost based on previous studies, and ended with the comparison of both scenarios to be further analyzed. The scheme is shown in figure 11.

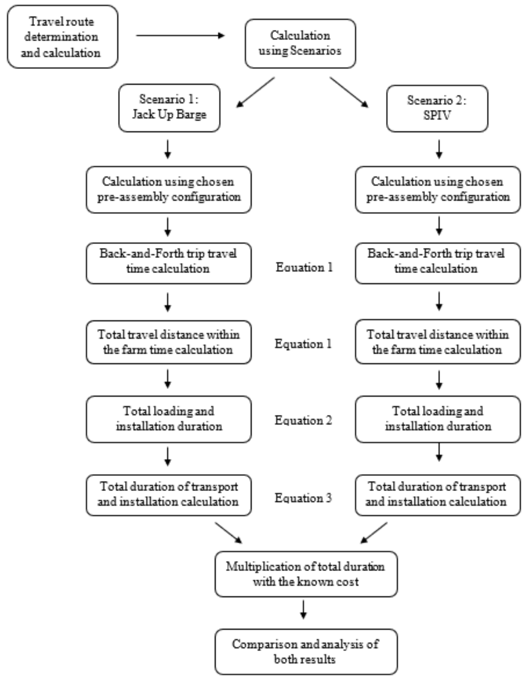


*Figure 11. Calculation Scheme*

With the distance ($D$) approximated, the last variable needed for the calculation has been obtained. From this point, the total transportation and installation duration can be calculated.

### 4.7 Total Duration of Wind Turbine Transport and Installation on Indonesian Sea Calculation

Since all the variables for the formula have been found out and determined, the calculation of the total duration of Transport and Installation of an offshore wind farm can be calculated. In this subchapter, the calculation will correspond to the different determined scenarios of transport vessels and configuration methods. Furthermore, the calculation of total time duration will be divided into 3 parts, Back-and-Forth trip, Total travel distance within the farm, and the assumption of the total duration of loading at the port and installation on site. Which will then be added together to fulfill the calculation of Total Duration of Transport and Installation, where it has been stated in *Equation 3*.

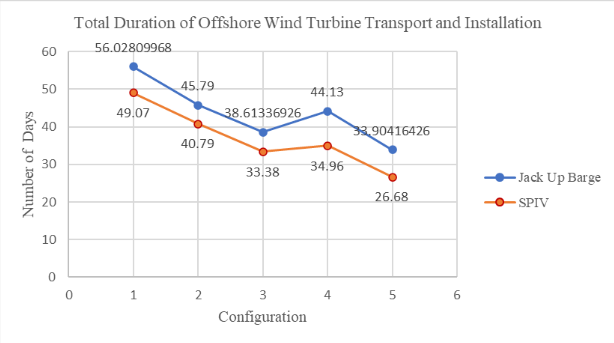


*Figure 12. Comparison of both Scenarios for the total duration*

### 4.8 Total Cost for Each Scenario

From [Tho14] the cost of the transport vessel is chartered daily. The daily charter cost is around €80,000 / day for Jack Up Barge and around €120,000 / day for SPIV. The calculated results must first be converted into days and then can be multiplied by the daily charter rate to see the total cost of each configuration for the different scenarios.

The exact number for the daily charter cost depends on the selection of the transport vessel. The number stated in this study is an approximation of the average daily charter cost of the Jack Up Barge and SPIV in 2014. It shows that the total duration of Transport and Installation for the Jack Up Barge transport is 34 Days with a total cost of €2,7 Million and for the SPIV transport vessel is 27 Days for the total cost of €3,2 Million.

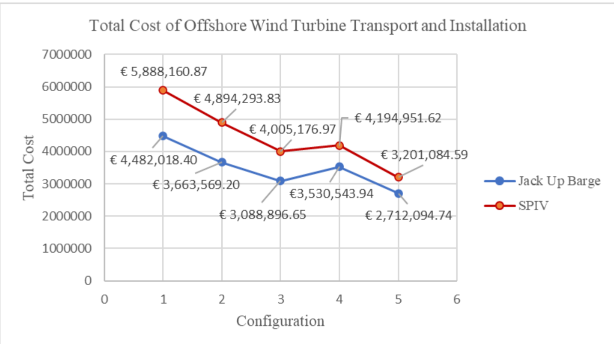


*Figure 13. Comparison of both Scenarios for the total cost*

Although the charter cost of a transportation vessel differs from each vessel, the calculation can be adjusted by replacing the approximated cost with the real cost of the transport vessel. This final calculation is for the cost of offshore wind turbine transportation and installation. More cost research and calculation needed, such as the offshore foundation and substation, must be done for the construction of offshore wind farms on the Indonesian sea.

### 4.9 The Comparation of Both Scenarios

Below is the analysis that the author has been made on this paper. The factor that decides the analysis from the author is the total cost, the number of durations, lifting numbers, differences of both scenarios in terms of total cost and duration, and a specific case. The analysis from the result of the calculation is not limited to the ones written on this paper. The analysis is shown below:

- The results show that the first scenario of using Jack Up Barge using the 5th configuration is the best choice in terms of the cost and duration of the project of 34 Days and a total cost of around €2,7 Million. Even though using SPIV is almost half a million more expensive, with the same configuration as the Jack Up Barge, it can save up to 7 days of the project. Costing around €69.500 / day to save up to 7 days.
- Although by having the same lifting number, for the specific case of Jack Up Barge, using the 3rd configuration is wiser than the 4th configuration. Because it can save up to 6 Days of total project duration and cost-saving of €500.000. The same thing applies to the SPIV transport vessel. With having the same number of lifts, the 3rd configuration has 2 Days of faster offshore wind turbine T&I and having €190,000 less cost than the 4th configuration.
- Using Jack Up Barge for the 2nd and 4th configuration yields almost the same result. The 2nd configuration having 2 days longer construction duration and cost €130.000 more expensive.
- The total duration of the 2nd and 3rd configurations of Jack Up Barge have 5 days differences with the same configuration of the SPIV scenario. These configurations have the least number of differences than the other configuration. The greatest number of differences in the duration is the 4th configuration of each scenario. SPIV finishing 10 Days faster with more cost of €663,000. Meaning, using SPIV as the more expensive choice is more reasonable for the 4th and 5th configuration.
- If by any means that the vessel cannot carry the whole wind turbine tower (must be split into 2 pieces), the first configuration is the worst possible choice. The 3rd and 4th configuration shows the best choice on this case. Even though the least cost for this case is the Jack Up Barge, with the 3rd and 4th configuration, it is worth considering using SPIV instead. Since the cost is not much higher than the 5th configuration SPIV transport vessel. Since SPIV has higher capabilities than

Jack Up Barge, SPIV has no problem lifting the whole wind turbine tower.

## 5 Conclusion and Recommendation

### 5.1 Conclusion

In conclusion, the optimal combination of the scenario for the transport cost of offshore wind farm installation on the Indonesian sea is by using the Jack Up Barge transport vessel with 1 whole turbine tower, bunny ear configuration, and the remaining turbine blade, or on this case can also be called the 5th pre-assembly configuration. The second-best choice for both scenarios is the 3rd pre-assembly configuration. Although it has the same number of lifts as the 4th configuration.

When considering using the more expensive choice, in this case, the SPIV transport vessel, the optimal cost is still the 5th configuration. But it should be noted that, when comparing the 4th pre-assembly configuration of both scenarios, the SPIV can save the most time. While the 2nd and 3rd configuration of both scenarios has the least number of different days.

### 5.2 Recommendation

To realize this study, more detailed variables, and research has to be conducted. Such as the weather probability, specific offshore site condition (wave height, and more detailed wind velocity), the Indonesian sea regulation, exact cost of the transportation vessel, energy needs of the region, the financial studies of the project, and other concerning studies. Until this study is made, there are currently no other studies of offshore wind farm construction projects on the Indonesian sea available. Other than that, most of the detailed information regarding the offshore wind farm project is not publicly available.

For the recommendation to improve the calculation itself, which corresponds directly to having the least transportation and installation cost, is by having a capable port near the offshore site. Along the coastline of south of Banten will greatly reduce the transportation and installation cost. There is no other capable port in the vicinity to support this project other than the chosen port when this study is made.

Even though with its limitation, this study can provide enough data on how to optimize the transport cost of offshore wind farm installation on the Indonesian sea and an approximation of the first Indonesian offshore wind farm if ever constructed.

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