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Literature Review of Installation Logistics for Floating Offshore Wind Turbines

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Purpose: *Currently floating offshore wind emerges as a new technology and thus making offshore windfarms in areas feasible where it was due to certain conditions (water depths, soil conditions) not feasible to install fixed offshore wind turbines. The installation process of floating offshore wind foundations is very different from fixed foundations and thus results in new installation processes.*

Methodology: *In this literature review papers over the last ten years with focus on floating offshore installation logistics will be identified and sorted by relevance, year of publication and quality. The publications will also be grouped into the different foundation types Semi-floater, Spar buoy and Tension-leg. These groups will be subdivided further into costs, technical or processes related to logistics.*

Findings: *The paper will show an overview of current processes and trends in installation logistics for floating offshore wind turbines. Currently the existing reviews lack for example scientific papers and supply chain requirements (Carbon Trust, 2015) or they are focused only on technical issues (Wang, et al., 2010).*

Originality: *This paper is original in the sense that currently no complete, thorough and up-to-date literature review for the installation logistics and the supply chain of floating offshore wind exists.*

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1 Introduction

The financial success of an offshore windfarm with floating structures depends to a high degree on the transport and installation phases and thus the use of appropriate processes. These processes differ from the transport and installation processes for fixed bottom offshore wind structures significantly. These processes also differ between the three different types of floating offshore wind structures (Weigell et al. 2019).

The levelized cost of Energy (LCOE) of offshore wind energy are very high. LCOE for the generation of a MW/h are between 129 EUR and 155 EUR in Europe (Noonan, et al., 2018) For projects in Germany in the year 2018 (Kost, et al., 2018) state a price of 75 EUR to 138 EUR per MW/h. The LCOE costs are defined as: “Levelized cost of electricity (LCOE) refers to the estimates of the revenue required to build and operate a generator over a specified cost recovery period” (U.S. Energy Information Adminstration, 2021).

Since most suitable areas were offshore wind energy will be installed in the future (the East Coast of the US, the West Coast of the USA and East Asia (China, South Korea and Japan) are not as shallow as the North Sea and the Baltic the need for the use of floating offshore wind structures will arise. Because these offshore wind farms will be installed in deeper water depths and farther away from land, floating structures will be of greater importance in coming years (Ferreño González and Diaz-Casas, 2016).

2 Problem description

The logistics of offshore wind is complex and subject to adverse environmental conditions. Floating offshore wind is a very new technology and not yet as matured as offshore wind farms using fixed bottom structures.

Currently there are only a handful of floating offshore wind projects and most of them are single prototypes in operation.

In this paper the authors will show a thoroughly overview over the current scientific literature regarding the installation logistics of floating offshore wind turbines.

It is not a surprise that due to new topic there are mostly “grey literature” by the involved companies available. Also some use cases on the internet by these companies. Additionally there is a great amount of literature in the form of standards and guidelines from classification companies like DNVGL (as of March 2021 only DNV) (DNV, 2021).

For example the DNVGL-ST-0119 – Floating Wind Structures is the main standard when in comes to floating offshore wind. There are off course also standards by the ISO, Class NK, the IEC and the American Bureau of Shipping.

Additional guidelines from DNV in the form of Recommended Practices (RP), Service Specifications (SE) and Standards (ST) are complementing the DNVGL-ST-0119. Examples are DNVGL-ST-N001 - Marine operations and marine warranty or DNVGL-ST-0054 - Transport and installation of wind power plants.

There are also several books who are very useful to familiarize with the topics. The publications of (Cruz and Atcheson, 2016) and (Castro-Santos and Diaz-Casas, 2016) give a stringent overview.

Nevertheless the scientific literature in form of journal publications and conference proceedings is not extensive at this time. Most of the current literature is of a very technical nature and does not deal with the installation logistics of floating offshore wind farms per se but more with loads and CFD (Computational Fluid Dynamics). Even these topics are important and of great interest they should not be the topic of this paper.

2.1 Basics and Definitions

2.1.1 Installation Logistics for Floating Offshore Wind

The processes for the installation logistics of floating offshore wind turbines are very different from the already established installation of fixed offshore wind farms. More processes are carried out on land or in the shipyard than at sea and thus leads to a different supply chain (Weigell, Deshpande and Jahn, 2019).

The following shows a the processes for the installation logistics based on the WindFloat project.

WindFloat is a single protype floating offshore wind turbine installed in the EEZ (Exclusive

Economic Zone) of Portugal. At the same time of the installation of the turbine the prelay "of the mooring was done by an anchor handling and tug supply vessel" (Cruz and Atcheson, 2016). The columns were then pre-assembled and moved to the dry-dock for assembling and then the turbine was moved to the installation site by the anchor handling and tug supply vessel (Cruz and Atcheson, 2016).

The process for this is shown in the following flow chart:

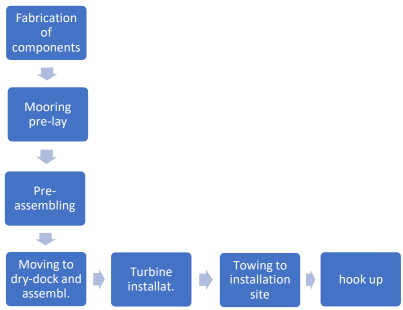

Figure 1: Installation Process Floating Offshore Wind Turbines

Source: Own representation based on (edp, 2015).

2.1.2 Types of Floating Offshore Wind Substructures

Currently there are three main types of floating offshore wind turbine set-ups to distinguish (Uzunoglu, Karmakar and Guedes Soares, 2016).

- Spar-Buoy
- Tension Leg Platform (TLP)
- Semi-Submersible Platfom

These three types are using different technologies to be stabilized in the ocean (Henderson, Collu and Masciola 2016).

- “TLP (Tension-leg Platform) where the floating platform is anchored to the seabed by vertical tensioners” (Díaz, Rodrigues and Guedes Soares, 2016)
- “Semi-sub (Semi-Submersible), where the platform gets most of its buoyancy from ballasted, watertight pontoons located below the free surface, providing very good stability characteristics” (Díaz, Rodrigues and Guedes Soares, 2016) and
- “Spar (Single Point Anchor Reservoir), where the platform is made of a vertical cylindrical floating body with a very large draft relative to its diameter.” (Díaz, Rodrigues and Guedes Soares, 2016)

(Uzunoglu, Karmakar and Guedes Soares, 2016) describe the technical properties in depths. Semi-Sub concepts are already in use in the oil and gas industry since the last sixty years and thus are proven concepts in terms of stability in waves especially for heaves and pitch. (Uzunoglu, Karmakar and Guedes Soares, 2016) The size and thus the loads which impact the structure are however different in floating offshore wind compared to oil and gas. (Uzunoglu, Karmakar and Guedes Soares, 2016). “The semi-submersible concept comprises of columns that provide the main volume under water and connecting members that provide structural integrity to the system as a whole.” (Uzunoglu, Karmakar and Guedes Soares, 2016)

The TLP concept was also first used in oil and gas in the 1980s. (Uzunoglu, Karmakar and Guedes Soares, 2016) The TLP is stabilized by mooring lines which are very stiff and thus resistant to motions. (Uzunoglu, Karmakar and Guedes Soares, 2016) “The typical TLP concept consists of a central column that carries the wind turbine with arms that support the tendons extending from the main body. The tendons are tensioned to provide stability. The number of arms and the angle between them may vary, usually being three or four.” (Uzunoglu, Karmakar and Guedes Soares, 2016)

The Spar-Buoy also has its origin in oil and gas and was first used in the 1990s. The Spar-Buoy is a cylindrical structure. “To provide stability, heavy ballast is used at the lower extremity of the platform, shifting the center of gravity to below the center of buoyancy. Station keeping is provided by catenary mooring.” (Uzunoglu, Karmakar and Guedes Soares, 2016) This concept is especially useful for very deep water depths due to the high weight at the floor of the cylinder which is working as an antagonist against roll and pitch of the structure. (Uzunoglu, Karmakar and Guedes Soares, 2016) It also has due to the cylindrical shape only small yaw motions and also a low stiffness in heave. The yaw forces have to be countered by the mooring lines. (Uzunoglu, Karmakar and Guedes Soares, 2016) Since this systems is targeted at deep water depths the mooring lines have to be very long which will lead to increasing costs of these. (Uzunoglu, Karmakar and Guedes Soares, 2016)

(Ferreño González and Diaz-Casas, 2016) give a thoroughly comparison between the three concepts. The following lines show the different advantages and disadvantages of the three concepts.

The TLP has a low structural mass, has few mowing parts and a high stability. Another advantage is that the turbine can be assembled in port. The disadvantages are however that the installation process of the substructure is very complex and thus there is the need for specialized installation vessels. Due to the technical nature of the TLP there are also high loads on the anchors and the mooring which fastens the TLP. (Ferreño González and Diaz-Casas, 2016)

The Spar-buoy is compared to the other systems less complex and thus can be used for serial production, it requires no active ballasting and the stability of the whole system is very high. (Ferreño González and Diaz-Casas, 2016) There are however the following disadvantages: the Spar-buoy can only be used in very deep waters, for the assembly of the turbine specialized vessels with dynamic positioning capabilities and heavy lift cranes are needed and finally the “large draft limits [the] ability to tow the structure back to port for major repairs.” (Ferreño González and Diaz-Casas, 2016)

The Semi-Submersible can be used in shallow depths and thus give a wider application range than the other floating sub-structures. The installation process is very easy since no specialized vessels are needed, just tug boats and the turbine can be assembled in port as well as major repairs can be carried out in port. (Ferreño González and Diaz-Casas, 2016) The disadvantages are that the Semi-Submersible has a very high structural mass, the structure is with many welded joints very hard to produce and the costs of the active ballasting is also very high. (Ferreño González and Diaz-Casas, 2016)

Based on the current distribution of the planned and fulfilled projects as well as prototypes there is a relatively evenly distribution of the three concepts and the best concept will be based on the particular project and location.

3 Research Methodology

3.1 Literature Review

In this step a structured literature research was done.

To the knowledge of the authors this was the only thoroughly done literature overview over floating offshore wind issues regarding the topic of installation logistics. Nonetheless the paper by (Wang, et al., 2010) looks at the topic of floating offshore wind more from a technical standpoint and less from logistical standpoint. Since the paper is more than ten years old and it is written from a technical standpoint it gives some insights but is not that suitable for the task of this paper. The technological advances for floating offshore wind over the last decade were big. Nevertheless the paper of (Wang, et al., 2010) is helpful to start from because the paper explains thoroughly the different design concepts of floating offshore wind.

In this paper only the logistical part installation of floating offshore wind turbines should be discussed. So all papers which handle the topic of fixed offshore wind structures have to be excluded from the search. Additionally all papers which cover pure technical topics and financial topics of floating offshore wind have to be excluded to. Only Journal articles and other scientific books were included in the search. So all grey literature and internet sources were also discarded from the search. Additionally books and book chapters were also not reviewed.

That leaves peer-reviewed journal articles and conference proceedings which are subject to this literature review. Only journal paper published in English were examined.

Due to fact that the research on logistics for floating offshore wind turbines is still relatively new, the snowballing approach according to (Wohlin, 2014) was used.

The following databases were used for the search were Google Scholar, Web of Science and Scopus.

The following keywords / terms were used: “floating offshore wind”, “logistics”, “supply chain", "installation", "transport", "Spar-Buoy", "Tension Leg Platform (TLP)", "Semi-Submersible Platform" and combinations of these. These resulted in a very high number of publications which had to be narrowed further down. The following shows this as an example for Scopus.

In Scopus there were 3,328 hits for "floating offshore wind", so this was narrowed down to 338 hits for the combination of floating offshore wind" and "installation". Furthermore all publications related to oil and gas were excluded using the limiter keywords "Offshore Wind Turbines", "Wind Turbines" "Wind Power" and "Offshore Wind Farms". This resulted in 274 papers. Furthermore the search was narrowed down to the key word "Floating Wind Turbines". This lead to 56 journal papers. For these 56 papers the abstracts were thoroughly analyzed. After this analysis 22 articles the result. 9 of these 22 articles were further deleted because there content was of a very technical nature and covered the logistics aspect of floating offshore wind turbines to a miniscule degree.

The procedure was done is a similar way for Web of Science and Google Scholar.

After these three databases were analyzed and duplicates were discarded a total of 30 relevant papers was the result. These publications are shown in Tab. 1

3.2 Classification of the literature

The following classification was used to systematically structure the particular literature.

The papers were grouped in the following areas:

Most publications regarding floating offshore wind deal just with the technical and engineering side. Since that floating offshore wind is a relative new technology this is not a surprise. Regarding the installation logistics of floating offshore wind most publications are from a company level and thus "grey literature".

The topic is not extensively discussed in the scientific community at this point. Comparing this to installation logistics for fixed offshore wind turbines it is reasonable to assume that this will change in the near future.

In the papers five groups were identified: General, Planning, Costs, Transport & Installation and Resources. The groups General and Costs stand alone, whereas Planning has four sub-groups, Transport & Installation has two sub-groups and Resources also has two sub-groups.

- General
- Planning
  - Model
  - Prototype
  - Design
  - GIS / Simulation
- Costs
- Transport & Installation
  - Installation
  - Processes
- Resources
  - Vessels
  - Anchors, Moorings, Cables

Table 1: Classification of the literature (Own representation)

	General		Planning		Costs		T&I		Resources	
Authors	General	Model	Prototype	GIS / Sim.	Design	Costs	Installation	Processes	Vessels	Anchors et al.
(Diaz and Soares, 2021)		X		X						
(Ren, et al., 2021)								X	X	
(Crowle and Thies, 2021)							X			
(Barter, Robertson and Musial, 2020)						X				
(Baita-Saavedra, et al., 2020)					X	X				
(Umoh and Lemon, 2020)	X									
(Stefanakou, et al., 2019)		X		X						
(Castro-Santos, et al., 2019)		X		X						

	General		Planning		Costs		T&I		Resources	
Authors	General	Model	Prototype	GIS / Sim.	Design	Costs	Installation	Processes	Vessels	Anchors et al.
(Weigell, Deshpande and Jahn, 2019)				X			X			
(Fontana, et al., 2018)						X				X
(Jiang, et al., 2018)						X	X			
(Castro-Santos, et al., 2018)						X				
(Campanile, Piscopo and Scamardella, 2018)					X	X				
(Fontana, et al., 2018)						X	X			X
(Hallowell, et al., 2017)								X		X
(Matha, et al., 2017)							X	X		
(Fujii, et al., 2016)							X			X

	General		Planning		Costs		T&I		Resources	
Authors	General	Model	Prototype	GIS / Sim.	Design	Costs	Installation	Processes	Vessels	Anchors et al.
(Castro-Santos, 2016)						X				
(Viselli, et al., 2016)			X							
(Castro-Santos, et al., 2016)						X				
(Castro-Santos, Martins and Guedes Soares, 2016)						X				
(Díaz, Rodrigues and Guedes Soares, 2016)						X				
(Campos, et al., 2016)								X		
(Taub, et al., 2015)						X				
(Tande, et al., 2015)	X									

	General		Planning		Costs		T&I		Resources	
Authors	General	Model	Prototype	GIS / Sim.	Design	Costs	Installation	Processes	Vessels	Anchors et al.
(Castro-Santos and Diaz-Casas, 2015)						X				
(Rodrigues, et al., 2015)					X					
(Utsunomiya, et al., 2014)							X	X		
(Castro-Santos and Diaz-Casas, 2014)						X				
(Taub, 2014)						X	X			
(Shin, Cho and Jung, 2014)		X								
(Collu, et al., 2014)							X			
(Utsunomiya, et al., 2013)			X							

	General		Planning		Costs		T&I		Resources	
Authors	General	Model	Prototype	GIS / Sim.	Design	Costs	Installation	Processes	Vessels	Anchors et al.
(Dymarski, Dymarski and Ciba, 2019)							X	X		

Fig 2. shows the number of publications per year:

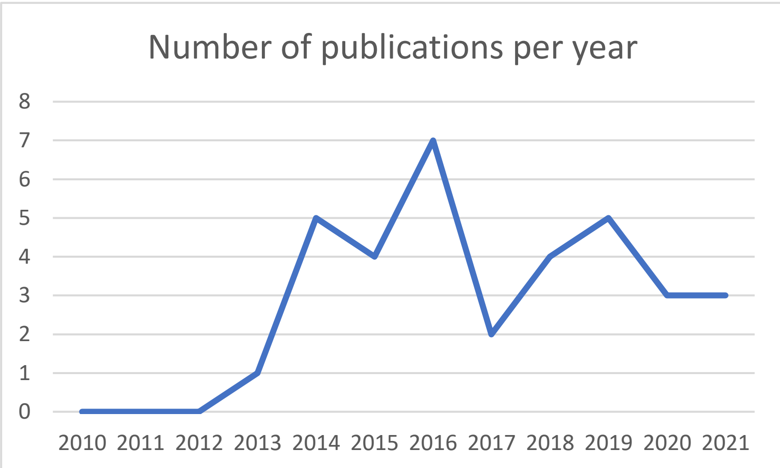

Figure 2: Number of publications per year

Source: Own representation

Interest in the topic started to gain traction in 2014 and there is a peak in 2016 with 7 papers. Due to the overall very small number of papers the trend at this point is not very meaningful. It is reasonable to assume that with more real projects starting in the near future there will also be an increase in publications.

4 Findings

4.1 General

Of the analyzed journal articles there are three journal articles which cover the topic of installations logistics for floating offshore wind in a general overview way. (Diaz and Soares, 2021) for example use multi criteria approach to evaluate different possible areas for floating offshore wind off the Canary Islands. (Umoh and Lemon, 2020) compare in their paper possible chances and obstacles for the use of offshore wind in Scotland (as an already mature market for offshore wind in general and also with the first floating offshore windfarm in the world in operation) with a new market (South Africa). Papers which were not treating the installation part (like technical publications or publications about the operation and maintenance phase) were excluded from this literature overview.

4.2 Planning

Since there is only a limited amount of already installed floating offshore wind projects and thus there is not an established state of the art way to install floating offshore turbines by now several approaches which involves planning were discussed in the publications. The authors divided the publications in the planning group further in the following subsets: Model, Prototype, Geographic Information System (GIS) / Simulation and Design.

(Stefanakou, et al., 2019) created a model for decision support using GIS for the installation phase of FOWT in the waters of Greece. Their findings lead to the conclusion that only small amount of installation sites in the Aegean Sea are feasible for FOWT. (Castro-Santos, et al., 2019) used a very similar approach to identify suitable installation sites off the coast of Portugal. (Diaz and Soares, 2021) developed a model were GIS was coupled with Multiple Criteria Decision Methods (MSDM) to identify the best installation sited for FOWT around the Canary Islands in the Atlantic.

The papers by (Viselli, et al., 2015) and (Utsunomiya, et al., 2013) are discussing the use of prototypes for site selection and for the installation of FOWT. The first one for the VolturnUS off the coast of the US state Maine and the second one is describing procedures for a location in Japan. (Shin, Cho and Jung, 2014) also use a prototype to show its unique installation procedures.

(Rodrigues, et al., 2015) develop a unique design concept to install FOWT by using moveable FOWT to optimize the layout of the offshore windfarm. (Baita-Saavedra, et al., 2020) propose a new floating offshore structure design made from concrete to reduce the installation costs. (Weigell, Deshpande and Jahn, 2019) did a simulation model for the installation processes of a semi-submersible offshore floating platform using the simulation software Anylogic.

4.3 Costs

With 14 publications costs are the biggest topic of the analyzed papers. Since the costs of floating offshore wind energy is currently very high to fixed offshore wind energy or other means of energy generation it is sensible that authors are researching on different approaches to reduce the costs of floating offshore wind energy and to make it more competitive. The following paper are among other items focusing on the installation costs of the LCOE (Levelized Costs of Energy) were installation / logistic costs are a big part of.

Castro-Santos is with six publications especially prolific in this area. She is discussing a broad spectrum in regard to costs of the installation of floating offshore wind turbines. Whether it will be (Castro-Santos and Diaz-Casas, 2014) were the authors analyzed the life-cycle costs of energy, where installation costs are an important factor, (Castro-Santos and Diaz-Casas, 2015) were the authors are doing sensitivity analyses of FOWT or (Castro-Santos, et al., 2018) were the authors develop a methodology to estimate the costs of Floating Offshore Wind Farms. In (Castro-Santos, et al., 2016) the authors develop a model where all relevant costs including transport and installation costs for FOWT are broken down and the authors test their model using a case study with floating offshore wind turbines of the coast of Galicia in Northern Spain. In (Castro-Santos, 2016) put more emphasis on decision variables for the cost model. (Díaz, Rodrigues and Guedes Soares, 2016) also did a cost assessment for a FOWT installation off the northern coast of Spain.

4.4 Transport and Installation

The topic Transport and Installation is divided in the parts Transport & Installation (T&I) and Processes.

(Weigell, Deshpande and Jahn, 2019) show the installation processes of a semi-submersible floating offshore platform. (Crowle and Thies, 2021) give in their publication a very good overview over processes like the processes in the dry dock, the temporary phases during the transport at sea, and the durations of the installation. (Collu, et al., 2014) give a good overview over processes during the transport and installation phase. A very big emphasis is in this publication on stability requirements during the different phases. (Jiang, 2021) gives a very extensive overview over installation processes for offshore wind in general and in this paper there is brief section on installation processes for Spar, Tension Leg Platform and Semi-Submersibles floating offshore wind structures. (Taub, 2014) proposes an system which uses innovative transport and installation processes to lower the Levelized of Energy of floating offshore wind by 10%-15%.

4.5 Resources

Regarding resources there is a much larger emphasis on moorings and anchors than for example vessels. In contrary to fixed offshore wind energy installation this is plausible because floating offshore wind turbines will be brought to the installation site by tug boat whereas for the installation of fixed offshore wind large und more expensive offshore installation vessels are needed. However for the installation of floating offshore wind the installation of the mooring lines and the anchors to install the floating offshore wind turbine are the challenging part.

(Campanile, Piscopo and Scamardella, 2018) develop in their publication suitable mooring designs for the use in medium and deep water depths for floating offshore wind.

(Fontana, et al., 2018) investigate two new anchor systems, one with three mooring lines and one with six mooring lines. In these systems the anchors will be shared by floating offshore wind turbines to lower the costs. In (Fontana, et al., 2019) the authors expand the anchoring system. (Hallowell, et al., 2017) take a look at how reliable a shared anchor system would be.

5 Conclusions

This literature review can only show a current state. This topic is very new and is getting traction over the last years and supposed to be getting more speed over the near future because of more projects in the United States, Japan and Korea. Also it can be said that some of literature for the first demonstration projects were published in Korean or Japanese. Additionally because the topic is new there is a great amount of “grey literature”, books and description of company websites but unfortunately not so many peer reviewed publications. Of these peer reviewed publications the vast amount is from a very technical standpoint and not from a installations logistics standpoint.

The authors structured the papers in the aforementioned five categories: General, Planning, Costs, Transport & Installation, and Resources with sub-categories. Since there is not really a state of the art and some papers tried to put a lot of very important information in the paper there was a high difficulty to separate the papers by these five categories so that some papers a fit more than one category.

The floating offshore wind would definitely benefit if more peer-reviewed scientific publications would be discussing the topic of installation logistics for floating offshore wind turbines.

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