Poulsen, T., Rytter, N.G.M., Chen, G.: *Offshore Windfarm Shipping and Logistics – The Danish Anholt offshore windfarm as a case study*, conference proceedings of 9th EAWE PhD Seminar on Wind Energy in Europe, September 18-20, 2013, Uppsala University Campus Gotland, Sweden.
http://space.hgo.se/eawephdseminar/?q=node/1

［中文］海上风电场的相关物流运输一丹麦 *Anholt* 风电场案例研究，作者托马斯.鲍尔森，尼尔斯.吕特，陈刚， 发表于第九届欧洲风能博士论坛，2013 年 9 月 18 日至 20 日于瑞典乌普萨拉大学 http://space.hgo.se/eawephdseminar/?q=node/1

OFFSHORE WINDFARM SHIPPING AND LOGISTICS – THE DANISH ANHOLT OFFSHORE WINDFARM AS A CASE STUDY

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ABSTRACT

In the relatively immature wind industry, it is extremely difficult to obtain a complete overview of the construction process, the related logistics operations, and costs involved in an E2E, cradle-to-grave windfarm life-cycle. This paper uses an extensive exploratory study performed by the first author to describe high-level shipping/logistics/SCM challenges faced in windfarm development by industry players. Subsequently, the Anholt offshore windfarm case study experiment is presented to validate the exploratory study. The paper concludes that better supply chain planning and more research efforts are needed.

NOMENCLATURE

DKK	Danish Kroner
EUR	Euro
GW	giga-Watt
km	kilometer
m	meter
MW	mega-Watt
t	ton
USD	United States Dollars

Abbreviations

BOP	Balance of plant
CLV	Cable laying vessel
EPC	Engineering, procurement, and construction company
E2E	End-to-end
HLV	Heavy lift vessel
JV	Joint-venture
LCoE	Levelized Cost of Energy
MP	Monopile
OEM	Original equipment manufacturer
RO/RO	Roll-on/roll-off vessel
ROV	Remotely operated vehicle (cables)
SCM	Supply chain management
SWP	Siemens Wind Power
TEQ	Transport Equipment
TP	Transition Piece
WTG	Wind turbine generator
WTIV	Wind turbine installation vessel

INTRODUCTION

Reducing the LCoE is a top priority for the wind energy industry in order to make wind power a viable, stand-alone alternative to nuclear energy and fossil fuels. With the first WTG entering into serial production only in 1979, the industry is still relatively young and no single OEM or BOP manufacturer has achieved a platform leadership position (Cusumano & Gawer, 2002). Unlike for example the automotive industry, the wind industry is still lacking industry standards and best practices in general and within the various production, installation, and operations disciplines. Different wind sub-suppliers as well as OEM's treat their designs, intellectual property, and product specifications in a very confidential manner which has a lot of ripple effects downstream in the value chain.

From an electricity output perspective, the development of WTG technology has been rapid: The first WTG's produced an output of less than 0.5 MW and could be shipped in a 40' container. As of mid-2013, onshore WTG's being installed produce some 1.5 – 3.5 MW and offshore WTG's generally produce between 3 and 6 MW. To achieve such an output increase, WTG's have grown exponentially in size and weight. This has had a tremendous impact on the supply chain facilities, TEQ, and logistical set-up required for moving both inbound assembly parts/components as well as outbound WTG and BOP modules. For example, the blade length of the Samsung prototype 7.5 MW offshore WTG measured an impressive 83.5 m and the Vestas 8 MW offshore nacelle is estimated to weigh approx. 380 t (BTM Consult part of Navigant & Poulsen, 2012).

With designs of WTG's and BOP modules taking place in relatively confidential design environments, the shipping and logistics industry is often included in planning efforts somewhat late compared to when significant TEQ investment decisions are made. Conversely, substantial LCoE reductions are expected from shipping and logistics activities by the contracting parties such as utilities, windfarm operators, EPC's, and OEM's. Pressure is thus asserted onto the shipping and logistics service providers from other major supply chain constituencies and this is evidenced in the form of both task allocation, risk sharing, and contracting.

In this paper, we first wish to bring forward relevant, original research from an extensive exploratory study which highlights opportunities to save costs within shipping/logistics/SCM related tasks (Christopher, 2010) with an aim towards reducing the overall LCoE. Second, we wish to use the Anholt offshore wind park case study to provide an overview of the construction phase of an offshore windfarm with a special focus on shipping, logistics, and SCM to contrast/confirm challenges, learnings, and opportunities for future cost savings with the exploratory findings.

METHODOLOGY

The key research question of this study is: What are typical shipping/logistics/SCM challenges experienced during a windfarm life-cycle? This question has been addressed based on extensive studies of the renewable energy market place from a shipping and logistics perspective as well as a series of interviews and site visits.

In order to identify the main shipping/logistics/SCM challenges, a comprehensive exploratory study was performed by the first author of this paper from 2010 to present. During the exploratory study, discussions during meetings, conferences, and as part of site visits took place with more than 300 interviewees and these interviews have generated an understanding of the wind industry's transport and SCM challenges faced and how costs may be reduced.

To experiment with how the identified exploratory study challenges are represented in a real case, more detailed interviews with key personnel from the supply chain constituencies involved in the construction of the Anholt offshore windfarm were conducted. Along with other data sources, various documents collected, as well as PowerPoint presentation materials, the additional interviews have formed the basis for creating a case study about the shipping and logistics efforts rendered during the Anholt windfarm construction phase. A total of 10 encounters involving approx. 30 different people formed the Anholt case study interview base and this included two field trip site visits.

All discussions were carried out as semi-structured interviews where the questionnaires were developed in an iterative manner and this was necessary as more information and knowledge was gained during the process (Brinkmann & Kvale, 2009).

EXPLORATORY STUDY

The interviews forming part of the exploratory study have been conducted on a global basis with an overweight of interviews conducted in Europe, some in Asia, and also some in the Americas. Based on the logic of the "middle-up-down management process" (Nonaka & Takeuchi, 1995), the interviewees have been selected from different organizational layers in order to ensure representation from a strategic top management perspective, a middle management point of view, and a more tactical perspective from the analyst/execution stance.

From the exploratory study, a number of conclusions could be derived as follows:

First, the windfarm life-cycle can be divided into 4 phases as described by Poulsen *et al*, (*forthcoming*) based on two industry research sources (BVG Associates, 2011, BTM Consult part of Navigant & Poulsen, 2012,):

- Development & consent
- Installation & commissioning
- Operations & maintenance
- De-commissioning

Second, a series of challenges face the wind energy industry from a shipping, logistics, and SCM perspective. The exploratory study has identified 30 key challenge themes which can be segmented into 4 main categories (Poulsen *et al*, *forthcoming*), namely macro economy and policy, supply chain economics, supply chain facilities/TEQ, and Supply chain operations.

Third, for offshore windfarms, operations at sea are generally much more time consuming and costly compared to onshore windfarms. However, no exact estimates are available when it comes to the total shipping, logistics, and SCM costs of an end-to-end windfarm throughout the 4 life-cycle phases. A reliable estimate of such costs up to 2050 was cited as "extremely relevant" by most interviewees for several reasons:

- Asset investments in ocean going vessels, ports, and land-based storage facilities take quite some time to mature and are often depreciated over 20-30 year time periods.
- Costs for the contracting supply chain constituencies such as utilities, operators, EPC's, and OEM's equal the revenue opportunity for shipping/logistics/SCM providers.
- Although viewed as an industry heavily depending on government subsidies, a strong and fully committed project pipeline exists at least 10-15 years into the future.

From the comprehensive literature review performed as part of the exploratory study (Poulsen *et al*, *forthcoming*), it was evident that additional support from academia is required in order to aid the necessary industrialization which is required in the coming years. Also, the shipping and logistics industry should be included much earlier in the process when it comes to the investments in various transport assets and TEQ used in the E2E windfarm supply chain. During the engineering and design phase of both WTG and BOP modules, all supply chain constituencies responded that a more integrated and synergistic collaboration would be beneficial. This would enable faster execution of the shipping/logistics/SCM work efforts rendering during all four phases of the windfarm life-cycle.

ANHOLT WINDFARM CASE STUDY

The Anholt offshore windfarm is located in the Danish Kattegat Sea between the peninsula of Djursland and the island of Anholt, see Fig. 1 below. The windfarm is located some 15 kilometers from the service port of Grenå and covers an area of 88 m^2.

Figure 1: Map of the Anholt offshore windfarm (Source: MTH)

The windfarm is owned 50% by Danish utilities company DONG Energy in JV with PKA and PensionDanmark. The windfarm is operated by DONG Energy and consists of 111 offshore WTG positions installed at 15.5-18 m water depth and all supplied by OEM SWP. Each WTG is capable of yielding some 3.6 MW power and at a total output of 400 MW, the Anholt windfarm is able to provide electricity to 400,000 households. This is equal to some 4% of the total energy consumption need of Denmark (DONG Energy, 2013).

The Anholt offshore windfarm is operated by DONG Energy under a 25-year operating contract and supplies power to the Danish national grid operator, EnerginetDK. The windfarm has cost approx. DKK 10 billion for DONG Energy to build (~USD 1.5 billion) and EnerginetDK has spent about DKK 1.5 billion (USD 250 million) to construct the substation and connect it to shore with export cables, equal to a combined total of approx. EUR 3.8 million per MW. DONG Energy has led the main windfarm construction using a multi-contracting set-up where DONG Energy has entered into contracts with several players directly (DONG Energy, 2013).

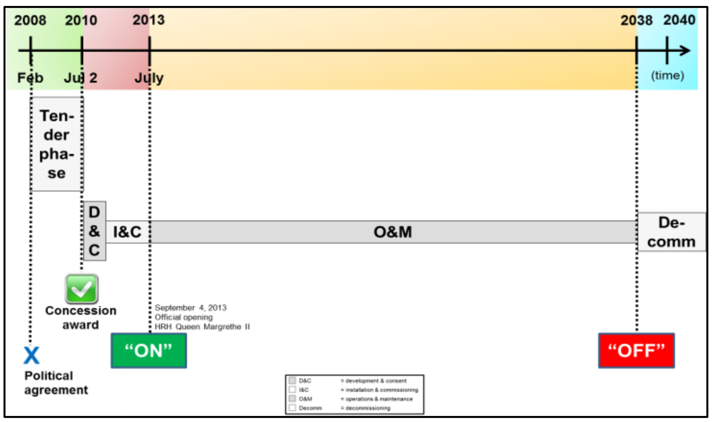

Figure 2: Anholt E2E life-cycle (Source: DONG Energy/research by authors)

Fig. 2 above shows a high-level timeline schematics of the total end-to-end project and confirms that the split of a windfarm into four life-cycle phases as identified in the exploratory study.

From a DONG Energy perspective, the speed with which the Anholt windfarm was constructed was quite fast compared to other windfarm projects due to several factors that reduced the overall complexity as follows:

a) DONG Energy has achieved a certain track-record and organizational experience level with offshore windfarm procurement, contracting, construction, and operations.
b) The offshore windfarm was constructed in the "home country" of DONG Energy and some of the key suppliers (Denmark). As such, transport distances were relatively limited compared to installations in e.g. UK or Germany.
c) The Anholt windfarm was constructed in relatively shallow waters and close to the coast. This should be contrasted to some of the deep-sea windfarms to be constructed very far off the coasts of both the UK and Germany.

When we examine the initial life-cycle phases a bit closer in Fig. 3 below, we see that the tendering phase was fairly short: One year was allocated from April, 2009 until April, 2010 in order for potential bidders to respond and the negotiations about the concession award were concluded in just over 3 months, on July 2, 2010. Two key milestones were included in the overall concession award: Power from the first installed WTG should be operational before the end of 2012 and the entire windfarm was to be operational before the end of 2013. Heavy daily fines would be levied to the successful concession holder if these milestones were not met. Already during this bidding phase prior to concession award, key DONG Energy contracting partners like EPC provider MTH have cited that they would have wished to be included to a greater extent in the planning process: Only such an integrated partnership model would enable MTH to start their process internally and with their partners much earlier and this would be key to both the overall cost picture, the quality of work, and the execution of the windfarm construction further downstream. In contrast, SWP had already in 2009 entered into an overall framework agreement to sell 500 3.6 MW WTG's to DONG Energy in order to alleviate the planning challenges. The 111 WTG's ordered from SWP by DONG Energy in the Anholt windfarm formed part of this framework agreement.

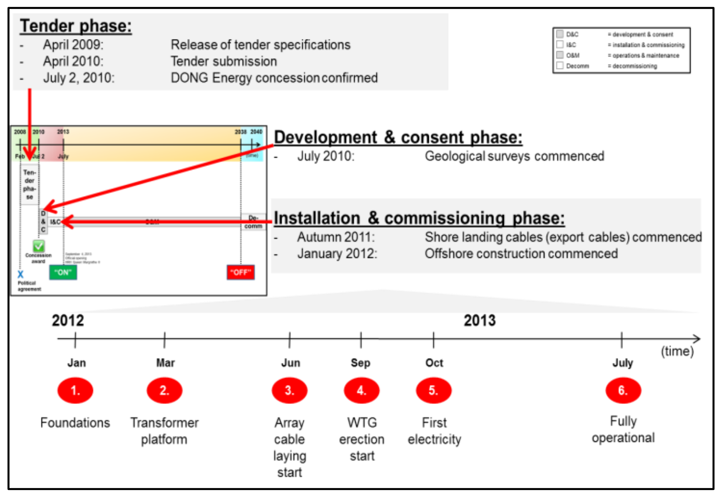

Figure 3: Initial Anholt windfarm phases (Source: DONG Energy)

Subsequently, a bit over a year was spent on the development & consent phase during which a couple of unexpected challenges occurred: DONG Energy had received a report on the seabed conditions from Danish Energy Agency (Energistyrelsen) as part of the tender. During the tendering phase, DONG Energy had identified that the report did not contain sufficient levels of detail and after the concession award, DONG Energy therefore performed additional surveys. These surveys revealed that the seabed was extremely porous and that many very large stones were located on the seabed and also imbedded in the seabed - both where MP's were to be installed according to plan and where WTIV's were supposed to jack-up to perform the installation. These findings made the downstream construction execution much more challenging.

Fig. 4 below summarizes the E2E supply chain complexity as it relates to shipping and logistics in the installation and commissioning phase of windfarm construction in terms of especially WTG and BOP modules. If the windfarm had been located further offshore at deeper water levels like e.g. planned German and UK windfarms, the complexity would have been even greater.

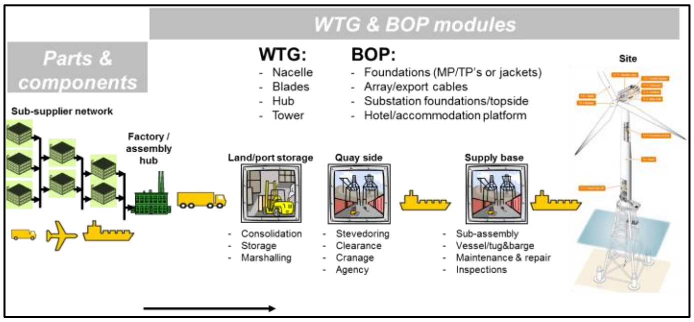

Figure 4: Supply chain complexity (Source: Author analysis)

The installation & commissioning phase was initiated with the laying of export cables commencing during the autumn of 2011 (contracted by EnerginetDK). As we further peruse the different installation & commissioning sub-processes, it is important to focus on the fact that export cables/substation were the responsibility of EnerginetDK and the balance windfarm construction the responsibility of DONG Energy.

While the export cables were in the process of being laid out, work on foundation installation commenced in January, 2012. MTH was contracted by DONG Energy to source, transport, and install the combined MP/TP foundations, each constructed in a bespoke and unique manner with an individual weight of between 350 to 550 t, depending on water depth and seabed porosity levels. Built by Bladt Industries in Aalborg for MTH, the MP's were first transported using tug boats from Aalborg to the offshore windfarm site. EPC company Ballast Nedam's HLV "Svanen" performed the MP installation and with a diameter of between 4.69 and 5.35 m at water depths of 15.5 – 18 m, significant cranage power was required for this task. "Svanen" furthermore hammered each of the MP's between 20 and 30 m into the seabed in order to ensure long-term stability of the WTG. The TP's were also constructed by Bladt Industries in Aalborg and for installation, Jumbo Shipping's HLV "Jumbo Javelin" was contracted by MTH. The vessel could load 9 TP's at a time directly from the port-located Bladt Industries plant in Aalborg and this enabled the on-board MTH personnel to lead the overall TP installation operations and perform the grouting process, effectively connecting the TP to the previously installed MP.

While the foundation installation process was still on-going, construction of the transformer platform/substation commenced in March, 2012 and lasted until August, 2012. By June, 2012, the laying and burying of array cables between the WTG positions commenced and some 8-10 WTG positions were serially connected in each so-called array strings. The cables were supplied by Nexans in Hannover and the cable drums were partly shipped to Grenå by truck, to Fredericia by train, and via train to Nordenham for subsequent transport on board Holland based Visser & Smit Marine cable laying barge "Stemat 82". Besides the "Stemat 82" barge propelled by 2 anchor handling tugs, CLV "Toisa Wave" also assisted with the laying of the approx. 159 km of cables produced in three different diameters. Each cable drum weighed between 12 and 40 t, depending on the cable diameter, and the "Toisa Wave" could carry 9 drums at a time. Cable laying finished by mid-September, 2012 and cable burial was completed by ROV jetting/trenching vessel "Swibe Else Marie" in February, 2013. In parallel to the cable burial process, diving support vessel "HBC Supporter" ensured that the cable protection seals were activated.

By September of 2012, WTG installation could commence with the 58.5 m long and 18 t heavy SWP blades transported in advance to the installation port of Grenå by road from the SWP blade factory in Aalborg. Similarly, the 205 t nacelle units were transported in sections from SWP in Brande with the nacelle, generator, and hub each transported separately to reduce the total weight load. The three 3-sectioned towers weighing in at a total of 200 t each were transported by truck from the outsourced tower sub-contractors of SWP in Give respectively Herning to the port of Horsens. From Horsens, the tower sections were shipped using RO/RO vessels to the Grenå port.

For the offshore installation process, special purpose WTIV's were supplied by the DONG Energy and SWP JV company, A2SEA, which had been acquired by DONG Energy in 2009 and subsequently sold in part to Siemens in 2010. Due to the porous seabed conditions coupled with the demanding installation time requirements of DONG Energy, DONG Energy had required that a minimum of 2 WTIV's be operational at any time at the installation port/offshore windfarm site. During the installation process, adverse weather and the poor seabed conditions forced A2SEA to mobilize a total of 4 different WTIV's with different capacities and capabilities. Different WTIV's had to be used at different times mainly due to the very varied seabed needs such as long thin legs for deep penetration to stabilize/avoid stones/jack-up or legs with a large spudcan area to stabilize the vessel in a porous environment. Also, one very new WTIV utilized was large and powerful enough to experiment with preassembling certain windfarm modules onshore thus optimizing the erection process offshore. Tests were carried out in terms of preassembling the towers at the installation port in Grenå, rather than putting the 3 tower modules and controller/power units together offshore in the harsh sea environment. These tests led to the identification of many potential future cost savings in the installation & commissioning phase.

Fully erected, what is visible to the eye is that each of the SWP 3.6 MW WTG's installed at the Anholt offshore windfarm protrude some 142 m above sea-level with a rotor diameter of 120 m and a total weight of some 460 t. Compared to an onshore windfarm, the BOP components both under water/stretching often deeply into the underlying seabed are integral parts of the windfarm construction, even though not directly visible from above sea-level.

The last of the 111 WTG's was installed by the end of May, 2013 and the windfarm was fully operational in July, 2013. The total windfarm construction time was just under 2 years with the official inauguration scheduled to take place on September 4, 2013.

LEARNINGS AND IMPLICATIONS

When we contrast and correlate the exploratory study and the Anholt case study, we find that the exploratory findings were largely confirmed.

The entry of larger, financially robust, and truly global shipping, logistics, and SCM service providers was generally cited in the exploratory study as a prerequisite for the shipping and logistics industry to be able to adequately lead and drive forward its' own industrialization process alongside that of the wind energy industry. In the case study we saw that DONG Energy and SWP had alleviated this challenge by acquiring a major player within the area of special WTIV's.

The case study also confirmed exploratory findings in terms of division of responsibilities and here, hand-offs between the various players in the supply chain and the resulting insurance/indemnification procedures are areas that continue to pose challenges whilst developing further during every offshore windfarm project.

In addition, the exploratory study cited that earlier and more integrated planning efforts are required in order for the windfarm development process to run more smoothly and to reduce costs overall. The case study confirmed that this remained a challenge for EPC provider MTH when it came to the contract to deliver and install MP's/TPs whereas SWP had alleviated this challenge to quite some extent by entering into an extensive framework agreement with DONG Energy about WTG supply.

Finally, being able to transfer best practices as well as lessons learned between offshore windfarm projects is a key objective cited by many of the interviewees in the exploratory study as well by the participants in the Anholt case study discussions and site visits.

A number of key observations from both the exploratory study and implications from the Anholt case study deserve mentioning. A key take-away from the Anholt case study is that from a planning perspective, there is a need to ensure that sufficient "buffer" time is available between the different sub-phases within the total construction plan and to always be prepared for the unexpected when it comes to break-downs, weather, and e.g. seabed conditions. Finally, health and safety concerns were cited in the Anholt case study as top priority practical implementation focus areas for further development along with the continued focus on reducing LCoE.

The exploratory study formed the basis for the creation of an initial shipping/logistics cost forecasting tool for one of the life-cycle phases of an offshore windfarm. For more details of the exploratory study, please see our previous study (Poulsen *et al*, *forthcoming*).

CONCLUSION

The Anholt case study has validated findings of the exploratory study and also provided more insights into detailed aspects of shipping/logistics challenges of wind farm construction projects. With the Anholt offshore windfarm case study, an initial experiment to validate the exploratory study interviewee input was made and at the same time, the case study described the construction phase in more detail even though the Anholt case took shorter time to complete and was less complex than other windfarm projects in deeper water and further from shore. The exploratory study yielded a number of high-level industry challenges from a shipping/logistics/SCM perspective and from a practical perspective during the construction phase, many of these challenges were confirmed in the Anholt case study. Exploratory study interviewees stated better supply chain planning that accurate cost forecasts are needed to ensure that the right asset investments are made. Finally, our findings revealed that additional research is required within global wind energy shipping/logistics/SCM to assist the industrialization of this important support function to the wind energy industry.

ACKNOWLEDGEMENTS

The authors of this paper wish to thank the many interviewees who have contributed to this paper by granting their time and knowledge as part of the encounters with Thomas Poulsen.

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