CURRENT DEVELOPMENTS OF WIND TURBINE INSTALLATION VESSELS

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1 INTRODUCTION

The first offshore windfarms in the 1990's were constructed close to shore and in shallow waters less than 10 meters in depth. They were constructed using mobile cranes on small jack-up barges supported by tugs and barges for trans-shipping of Offshore Wind Turbine (OWT) components. These barges and construction methods were usually employed in the construction of jetties and other coastal structures.

As windfarms moved further offshore and into waters deeper than 20 meters, large floating cranes were employed, but due to the lifting precision required to construct the OWT, the construction operations were often impossible in even the slightest sea swells resulting in lengthy delays and cost over-runs. Furthermore, the components still needed to be shipped separately adding to the construction costs. Clearly a better construction method was required.

The A2SEA *Sea Energy* was a converted general cargo vessel circa year 2000. With the addition of stabilising legs and crane the vessel was also able to carry the OWT components. Although this was a step in the right direction, the vessel could not lift itself free of the sea surface and was therefore still operationally limited by wave disturbance. In 2003 KNUD E. HANSEN designed *Mayflower Resolution*, which has been recognised as the world's first purpose-built Wind Turbine Installation Vessel (WTIV). Today, the world fleet of WTIV numbers over 50 vessels and with increasing demand for offshore wind energy there is a newbuild market for about 60 vessels with an estimated value of 14 billion USD over the next 5-10 years [1].

In this paper the author investigates the current trends in WTIV capability and design to meet the demands of the increasing size OWTs and more efficient construction methodology. The paper covers some of the unique naval engineering challenges that WTIVs pose to the designer that set this type of vessel apart from others. Finally, how 3D modelling and ShipSpace™ Virtual Reality collaboration tools are being used in the development and operation of the new generation of WTIVs.

2 BACKGROUND

2.1 OFFSHORE WINDFARMS

Offshore windfarms take advantage of offshore winds that blows stronger and more consistently than onshore winds. Typically, offshore windfarms have been:

- Within 50 nautical miles from coast
- Less than 50 meters water depth
- Array of 50 to 150 wind turbines
- Peak power = 200-2000 MW
- Cost = 50-100 USD/kWh

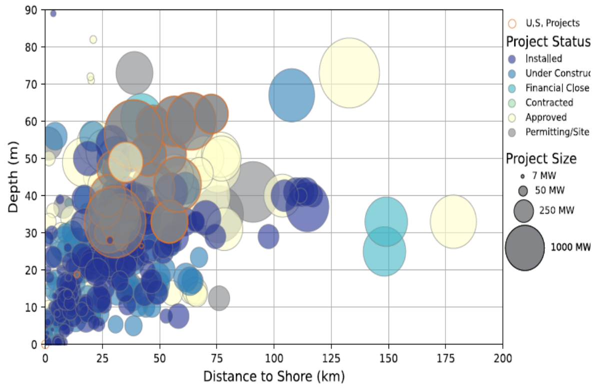

Figure 1 – Offshore windfarm principal particulars [2]

As can be seen in Figure 1, the trend is for offshore windfarms to become larger in capacity, further offshore – out to 100 nautical miles, and in deeper waters – up to 80 meters depth. These increases are mainly due to the advancement of OWT technology and the reducing availability shallow water areas with good wind resources. The maturing of construction methods and the growth of OWTs themselves have reduced the cost of installation from 200-300 USD/kWh to now less than 100 USD/kWh [1].

2.2 WIND TURBINE GENERATORS

Offshore Wind Turbines (OWT) have grown rapidly in size over the last 30 years. The first OWTs were able to generate 1000kW and had a rotor diameter of 30m. The current OWTs are able to generate 12-15MW with a rotor diameter of 220m and even larger 15-20MW OWTs are being developed. This growth trend will probably see some levelling off in the next decade as the limits of materials and economy-of-scale are reached.

Currently, almost all OWTs are of the fixed-bottom type. There are various types of foundations used including monopiles, jackets and gravity bases, depending on the water depth and seabed geology. Offshore windfarms are typically in water depths of up to 70-80m.

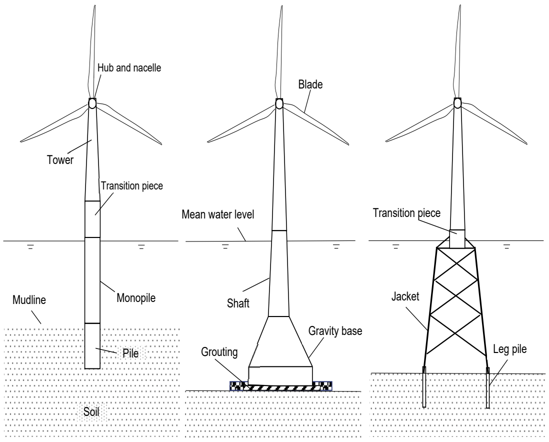

Figure 2 – Offshore wind turbine main components & foundation types [3]

Despite growing interest in Floating Wing Turbines (FWT) for waters deeper than 100 meters, there are only a couple of FWTs being tested and one pilot floating windfarm operating. All offshore windfarms in currently being planned are for fixed bottom OWTs.

2.3 WTIV CHARACTERISTICS

Although there is no formal definition of a WTIV, the main defining characteristics of a WTIVs are generally the following:

- Self-propelled & able to manoeuvre precisely
- Self-load & transport wind turbine components
- Self-install wind turbine components

It is worth noting that one of the principal operational concepts of WTIV is to be self-sufficient to eliminate the need for other support vessels. The term Jack-Up Vessel (JUV) is also used.

Figure 3 – Worlds first WTIV, MPI Resolution

The continuing growth of OWTs has also driven the growth of WTIVs. Designers at KNUD E. HANSEN Naval Architects have been at the forefront of WTIV developments. Following the first WTIV MPI Resolution, KEH developed the Pacific Orca and Pacific Osprey in 2008, which were the first WTIVs to be developed for 5-8MW size OWTs and water depths over 50m. Currently KEH is involved in the development of the next generation of WTIVs able to install the latest 12-15MW OWTs. The growth of WTIVs can be seen in the following table.

Name	Resolution	Pacific Orca	Atlas C
Year in service	2003	2013	2023
Length (LOA)	130 m	161 m	170 m
Moulded beam	38 m	49 m	60 m
Hull depth	8.0m	10.4 m	13.2m
Min. draught	3.4m	5.5 m	6.5m
Cargo area	2,800 m^2	4,500 m^2	6,800 m^2
Jack deadweight	2,000 tons	8,400 tons	18,000 tons
Crane max. load	300 t	1,200 t	3,000 t
Crane load height	100 m	140 m	160 m
Speed	10.5 kn	13.5 kn	12.0 kn
Installed Power	8,000 kWe	23,000 kWe	26,000 kWe
Typical cargo	10 x 2 MW OWTs	12 x 4 MW OWTs	6 x 15 MW OWTs

Table 1 – Principal particulars of some WTIV by KEH

One of the main problems facing owners of WTIVs is future proofing. The growth of OWTs has been so rapid that within 10 years many WTIVs have been unable to tender for construction contracts due to either water depth or crane load and height limitations. With the rapid WTIV fleet growth in the past 20 years, many owners choose to build to meet near-horizon market needs at the lowest cost and with limited ability to upgrade the vessels. Consequently, many of these WTIVs are not able to install future OWTs and will see-out their useful lives undertaking maintenance for existing wind farms.

3 OPERATIONS & LOGISTICS

3.1 TRANSPORT

Typically, a WTIV is required to transport all major components of the OWT to site and install them. This includes foundations, towers, nacelles and blades. Foundations are naturally transported and fixed in place first.

How the OWT components are transported has been the subject of much study and experimentation. It has been impractical to transport the OWT as a single unit due to the technical difficulties of lifting such a massive unit and acceleration limitations of the OWT when sea-fastened to the vessel.

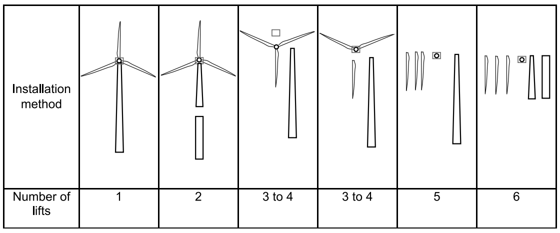

Figure 4 – Installation method & required lifts [3]

Towers were initially transported and installed in many sections, but today as a single unit. Likewise, the blades were initially been transported separate from the nacelle installed once the nacelle has been installed on top of the tower. In other OWF projects the blades have been shipped as a complete rotor assembly or as 'bunny ears' with two blades pre-assembled to the nacelle. Elaborate blade racks or rotor jigs are custom fabricated to support these delicate components.

The total number of lifts required to install a complete OWT is often used as a metric to determine installation efficiency and as a design driver for WTIVs and the OWTs themselves. For example, the WTIV is designed to take the high deck loads of a complete turbine towers, which in turn also need to be designed for the high acceleration loads of a WTIV in heavy seas. WTIVs can be quite stiff, given their wide beams compared to their draught and low GM.

Figure 5 – Nacelle being lifted onto a tower

However, reducing the number of required lifts is not necessarily a logistical benefit since the deck space required for sea fastening larger assemblies could be outweigh the benefit of requiring more lifts and on-site assembly. For example, a particular WTIV may be able to carry two 5MW OWTs each with two blades pre-assembled onto the nacelle but may be able to carry four turbines without blades attached.

The distance from the OWT staging or loadout port is another critical factor, since shorter distance may favour more pre-assembly, while a longer distance may favour carrying more OWTs even if they require more on-site assembly.

3.2 POSITIONING & JACKING

Having arrived at the windfarm construction site, the WTIV will engage its Dynamic Positioning (DP) system to manoeuvre into the desired location and position. The vessels thrusters must hold the position precisely while the legs are jacked down to the seabed.

After touch-down, the legs must be jacked down quickly to pin the vessel onto the seabed after which the DP system and thrusters can be secured. Typically, the spudcans will penetrate into the seabed by about 5 to 10 meters.

Once pinned, but before the vessel can be jacked above the sea surface, the legs will be pre-loaded one or two legs at a time to about 150% of the nominal standing load. Thereafter, if any leg experiences a seabed punch-through when the vessel is standing out of the water the remaining legs should be able to support the vessel.

The jacking height will depend on either clearing surface waves or raising the crane to increase the lifting height. Typically, a WTIV will jack at least 5 meters above the surface to ensure a rogue wave will not upset the vessel when jacked and during crane operations. Such a disturbance could result in severe damage or destruction of the legs or crane.

3.3 CRANE OPERATIONS

The WTIV can begin construction operations once securely jacked into position. When installing foundations piles, the main crane will lift the piles into a hull mounted pile gripper and then hammer the piles into the seabed with a hydraulic hammer.

More massive gravity and jacket foundations with suction buckets are lowered into position on the seabed. Other vessels may be used to pump water out of the suction buckets and laydown rock beds for scouring protection.

After the pile has been hammered into the seabed, the transition piece will be lifted and lowered over the pile and grouted into place. Gravity bases and jackets generally do not require a separate transition piece for attachment of the turbine tower.

The OWT topside construction can start after the foundations have been installed. This will usually involve the deck of the WTIV being stripped of foundation construction equipment and sea-fastenings and refitted for carrying OWT topside components – the towers, nacelles and blades.

Once jacked in position, the WTIV main crane will typically only require between 3 and 5 lifts to install the topside components and this is normally accomplished in a 24 hour day.

Custom lifting yokes for each component are used. The blade yoke has become increasingly complex to enable remote adjustment of blade tilt and rotation in many axes to compensate for wind loads and precise alignment with the hub fittings. A single blade for a 6 MW turbine is about 75 meters in length and weighs 25 tons.

3.4 UNJACKING

Once the cranes are parked in the boom rests and secured, un-jacking can begin. This process involves not just lowering the vessel back into the sea, but also extracting the legs out of the seabed which they may have penetrated up to a depth of 10 meters. See Section 4.2(c) for further discussion of spudcan design.

When the vessel is un-jacked and being supported by the sea, if leg extraction is difficult, legs may be partially extracted one or two at a time to ensure that the transition from pinned to thruster control can be achieved quickly. Often, an unjacked vessel will start moving to the next site with legs not fully retracted. This is to save time and use the motion of the vessel to clean away any seabed that may be covering the leg or spudcan.

4 SPECIAL DESIGN ASPECTS

4.1 DESIGN DRIVERS

The design of WTIVs is highly complex, due to the demanding operational requirements and the unusual necessity as a ship to function out of the sea. When trying to breakdown a complex problem, it is instructive to understand the primary requirements and how they relate to the main systems of the vessel. For a WTIV the main systems that effect the capability of the vessel are the hull, legs, crane and propulsion system. The importance and interdependencies of these systems to the WTIV capability can be seen in the following table.

	Design Drivers vs System	Hull	Legs	Crane	Propulsion
Cargo	Deck area	H	H	M	-
	Deadweight	H	H	M	M
	Lift load	M	H	H	-
	Lift height	-	H	H	-
Environment	Min. water depth (Navigating)	H	L	-	H
	Max. water depth (Jacking)	-	H	-	-
	Water current	M	L	-	H
	Wind speed	L	M	M	H
	Air draught	-	H	M	-
Performance	Vessel speed	H	L	-	H
	Jacking speed	-	H	L	L
	Maneuvering redundancy	L	-	-	H
	Punch-through redundancy	M	H	-	-
TOTAL	**Design Dependencies**	**20**	**29**	**15**	**18**
TOTAL	**System Interdependencies**	**96**	**107**	**74**	**71**

Table 2 – WTIV design dependencies

When the system interdependencies are tabulated and then expressed graphically, it becomes clear that the legs are the most important WTIV system in terms of both the vessels capability and also the effect on the other system.

Main System Interdependencies

	Legs	Crane	Prop.
Hull	40	20	36
Legs	-	43	24
Crane	-	-	11

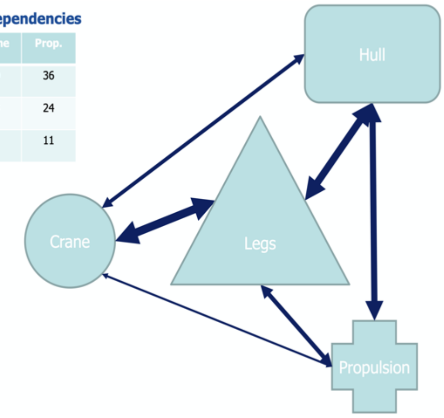

Figure 6 – Main system interdependencies

4.2 LEGS & JACKING SYSTEM

The two main design decisions for the legs system is the number of legs and type of leg. This is highly complex subject in itself, so the discussion here will be necessarily simplified.

4.2 (a) Number of Legs

There are a number of factors when considering the number of legs for a WTIV. These include:

- Effect on deck space
- Effect on hull shape
- Effect on hull strength
- Effect on leg load balance
- Effect on crane accessibility
- Stability of the jacked vessel
- Stability in case of leg punch-through
- Cost

Since the legs system can be nearly half the cost of the WTIV, there is a strong incentive to minimise the number of legs. The lowest practical number of legs for a WTIV is three legs. Although most vessels have four legs and some also have six legs.

3 Legs
(Shengping 001)

4 Legs
(Seajacks Scylla)

6 Legs
(Pacific Orca)

Figure 7 – Examples of various number of legs

Six legs provides for the best hull in terms of shape and strength and also is most stable and safe from punch-throughs. On the downside, having more legs places compromises on the deck space and crane accessibility and costs more.

It should be noted that while cost increases with the number of legs, it is not linear with fewer legs needing to be stronger. The pros and cons can be seen in the following table. Four legs are justifiably the most common.

	Deck space	Ship shape	Hull struct.	Load balance	Crane access	Jacked stability	Punch-through	Cost	TOTAL
Weight	M	L	L	L	M	H	H	M	
3 Legs	+	-	+	+	+	-/+	-	+	32
4 Legs	+	-/+	-/+	-/+	+	+	-/+	-/+	37
6 Legs	-	+	+	+	-	+	+	-	33

Table 3 – Number of legs & weighted score

4.2 (b) Type of Legs

There are two main type of legs used for jack-up vessels. Plate legs are normally built up from rolled or fabricated steel plates into cylindrical or square section legs. Plate legs use hand-over-hand jacking systems. Truss legs are built up from rolled tubular steel sections into a triangular truss structure. Truss legs use rack-and-pinion jacking systems.

Figure 8 – Plate legs (L), Truss legs (R)

For early WTIVs, plate legs where primarily used due to their lower cost. However, as demand for jacking in waters deeper than 40-50 meters has increased, truss legs have been favoured due to their lighter more efficient structure and faster jacking speed, albeit at a higher cost.

Compared to jack-up drilling rigs, that are designed to jack a few dozen times in its life, the legs of a WTIV must be designed for at least 2,500 cycles, with future vessels designed for over 5,000 cycles. This is generally achieved by increasing the number jacking motors to spread the load on the leg racks.

Rack-and-pinion jacking systems are also faster than hand-over-hand. This is especially important as WTIVs will spend much of their time jacking up and down.

4.2 (c) Spudcans

The spudcans at the foot of the legs must support the WTIV when jacked-up. They must be designed to cope with a variety of seabed conditions from silt and clay to sand and rock. The main design factors of the spudcan are their foot area and bottom shape.

Figure 9 – Spudcan & leg being lowered into leg well (Samsung HI)

The spudcan area will determine the ground pressure and seabed penetration. Typically, a WTIV will have a standing ground pressure of 40-60 tons per square meter. Larger spudcans are more costly and complicate the construction of the vessel if they cannot pass through the leg wells.

Harder clay type seabeds can be problematic if the legs do not penetrate deep enough. The spudcans could slide and cause the legs to bend. The spudcans bottom will often have a skirt or centre cone to prevent sliding on such seabeds. The seabed conditions and geology of each OWT installation site is already well understood from detailed surveying and studies when determining the suitability and foundation design. It may be necessary to modify the spudcans to suit the specific seabed condition.

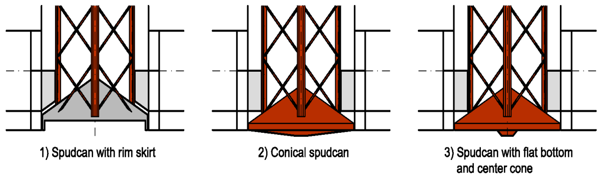

Figure 10 – Spudcan types [4]

In some vessels, the spudcans have buoyancy tanks to counter-act the weight of the leg and reduce the power required for leg retraction. Each leg can weigh many hundreds of tons. The spudcans can also have water or air jetting services to help them break the suction effect when extracting the legs out of the seabed.

4.3 HULL & DECK STRUCTURE

As can be seen in Section 4.1, the hull and leg systems have a high level of design interdependencies. The number and arrangement of legs have a direct effect on the cargo deck layout and the shape of the hull.

4.3 (a) Hull Lines

The hulls lines of a WTIV are challenging, since the most efficient shape for cargo layout and crane accessibility is where the length and beam are equal. Some WTIVs are designed with a barge type foreship with little or no attempt to streamline the hull. Other vessels, especially those with six legs, are decidedly more ship like.

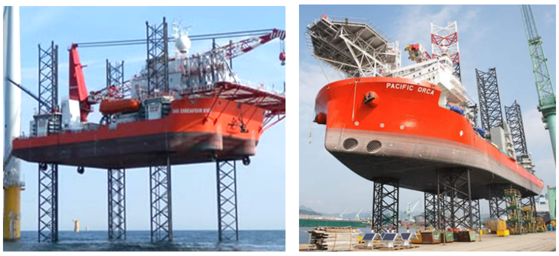

Figure 11 – Hull types, barge-like (L), ship-like (R)

WTIVs with barge shaped hulls are limited in speed to 8-10 knots, while those with more ship-like hulls are able to achieve 12-14 knots. While the difference may seem quite small, if the construction site is 100 nautical miles away, over the construction period for 100 wind turbines the time saved by the faster vessel could amount to a few months. As windfarms move further offshore, the vessel speed becomes even more significant.

Complicating the hull lines is the necessity to integrate thrusters into the bow and stern area to provide good manoeuvrability. This is covered further in Section 5 – Propulsion.

4.3 (b) Global Loads

The global structure of the hull must be designed for the required hogging and sagging wave forces while navigating but also the leg loads when jacked up. The dead loads can be highly variable depending on the how the OWT components are arranged on deck. Furthermore, the live loads must also be considered during crane operations.

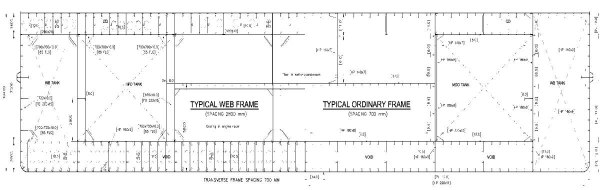

Figure 12 – Typical WTIV midship section [4]

4.3 (c) Local Loads

The cargo deck must be designed for heavy local loads and have the flexibility for different load outs including piles, jackets, towers and nacelles. To enable this a grid of deck hardpoints is arranged at regular spacing both longitudinally and transversely. Typically, such a grid would have a spacing of 1.5 meters and able to take a deck load of 10-20 tons per square meter. Additionally, due to the large acceleration loads that will be experienced, for example by 100 meter high towers in a rolling seaway, the deck must be designed to take both positive and negative vertical loads.

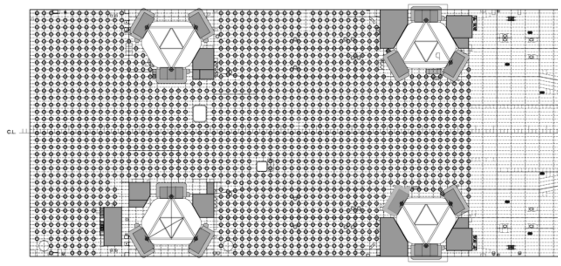

Figure 13 – Typical WTIV deck hardpoints [4]

The deck also needs to have a grinding allowance to for a lifetime of sea fastenings. A three millimetre allowance over an area of 5,000 square meters is over 100 tonnes of steel.

4.4 PROPULSION SYSTEM

The demands placed on the propulsion and manoeuvring system of a WTIV are significantly greater than for other vessels. These include:

- Dynamic positioning
- Thruster installation
- Machinery cooling
- Fuel systems

4.4 (a) Dynamic Positioning (DP)

With the need to manoeuvre precisely, WTIVs usually have a DP2 propulsion system to provide redundancy and safety in case of equipment failure, such as a generator engine or thruster. Higher specification vessels will employ at least four generators, three bow thrusters and three stern thrusters to achieve a reasonable DP2 performance.

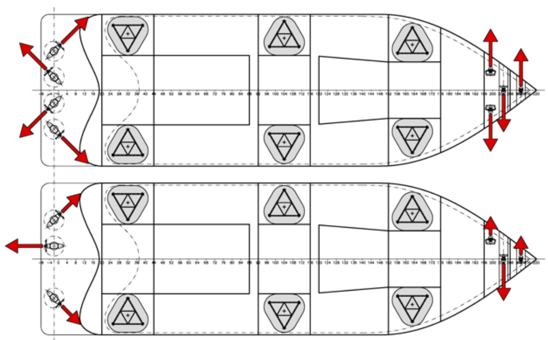

Figure 14 – Intact DP (T), Thruster failure (B) [4]

Dynamic Positioning modelling and control systems must be programmed for a vessel with a highly variable geometry. The forces from wind, waves and currents can change significantly when the legs are extended and retracted. The largest WTIVs have about 4,000 square meters of leg area exposed to wind and ocean currents. The required thruster force to counter a 40 knot wind load or one knot current on the legs alone is about 100 tons bollard pull.

During jacking operations, when the legs touch-down onto seabed the DP must be put into a low-gain control mode to prevent the thrusters fighting against the legs. The same applies to the transition between from being pinned by the legs to floating free when the legs are being retracted.

4.4 (b) Stern Thruster Installation

The barge like hull of the WTIV provides a number of challenges for installation of thrusters. At the stern, the wide beam and relatively shallow draft of the vessel can cause thruster ventilation when rolling in a seaway. An azimuth thruster can have a thrust loss of about 75% with just 5% propeller emergence. Thruster ventilation will result in impact loading on the transmission with potential damage and failure of gear teeth.

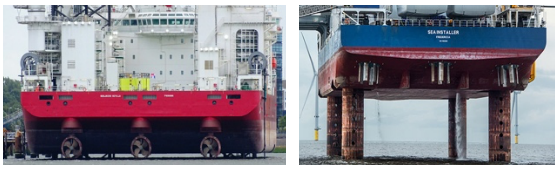

Figure 15 – Azimuth thrusters (L), Cyclic propellers (R)

By placing the thrusters closer to the centreline to reduce the occurrences of propeller emergence will reduce their effectiveness due to increased thruster shadowing. Many WTIVs are using podded thrusters with integral motors and no geared transmission, or cyclic propellers that are not adversely affected by thruster ventilation.

4.4 (c) Bow Thruster Installation

Installation of tunnel type bow thrusters on WTIVs is complicated by the wide beam and short foreship. Thrusters in long tunnels cannot produce full thrust due to frictional loses. Using azimuthing thrusters at the bow is difficult unless the thrusters are below the hull which would increase the vessel draught significantly from about 6 meters to 9 meters, which would limit operations in shallow coastal waters.

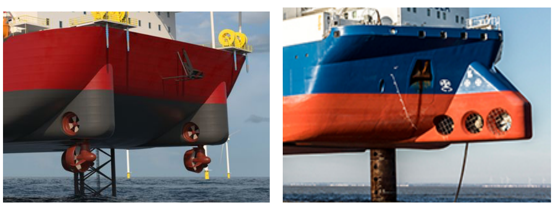

Figure 16 – Azimuth thrusters (L), Tunnel thrusters (R)

Many recent WTIV's are using a combination retractable azimuth thrusters and tunnel thrusters. Retractable thrusters are more complex and expensive but are necessary to provide adequate thrust at the bow without compromising shallow water operations. Directional stability of the short and wide WTIVs hulls is poor, especially in following seas and bow mounted azimuthing thrusters can be used to provide more effective course keeping.

An additional complication for thrusters on WTIVs is the shaft seals will undergo constant pressure cycling as they subjected to water pressures of up to 10 meters and then to atmospheric pressure when jacked-up. The thruster's lubrication systems must be designed for this operational cycling.

4.4 (d) Machinery Cooling

Ships use vast quantities of seawater to cool their machinery systems. Typically, for every megawatt hour of propulsion or electrical energy produced, a megawatt hour of heat is created and absorbed by the sea. When a WTIV is jacked-up, there is no direct access to seawater for cooling.

A number of solutions for machinery cooling have been used on WTIVs. Some early vessels used air-cooled radiators, although as the vessels became larger, this became impractical due to the size of the radiators needed. Some vessels use a closed-circuit seawater recirculation system in double-bottom tanks, with the hull bottom acting as a large radiator surface. The volume of seawater needed is considerable, hundreds of tons, and limits the deadweight available for the cargo. Cooling effectiveness also decreases as the ambient sea and air temperature increases to the point of being ineffective at about 20 degrees Celsius.

The method used by most WTIVs today is to use submerged pumps that are connected to the leg structure, or that can be lowered separately into the sea with flexible hoses and a reel management system. These pumps need to lift the seawater about 20-30m and are often driven by hydraulic motors and power packs adding to the complexity of the set-up.

4.4 (e) Fuel System

The load-out port is normally as close to the new wind farm as possible, so the time the WTIV spends in transit is minimised. Therefore, fuel consumption has not been a high priority for operators and designers. However, with increasing international commitments to mitigate climate change, operators are looking at ways to improve the green profile of their WTIV's.

Some of these initiatives include looking at greener fuels such as LNG and methanol. Although these fuels require a larger volume for the bunker tank because of gas fuel requirements and lower calorific value (methanol), finding adequate space within the vast WTIV hulls has not posed a problem.

The WTIV spends much of this time with generators running but only lightly loaded. This wasteful ‘spinning-reserve’ is needed for immediate power availability and not waiting for generators to be started. This normally happens when manoeuvring with thrusters or during crane operations.

Spinning-reserve can be usefully employed to charge batteries. Power from the batteries can then used when demand is high instead of needing another generator to be brought on-line. This concept is known as peak-load-shaving. Furthermore, rack-and-pinion leg jacking systems are able to recover about 60% of the jacking-up energy to batteries when the vessel is jacking down. A single jack takes about 10 megajoules of energy.

4.5 CRANE SYSTEM

The crane is the main tool of the WTIV and is well known in the market that crane capacity is one of the main limitations preventing current vessels from being hired. The main factors considered for the crane specification and installation on a WTIV are:

- Load radius
- Load height
- Crane installation

4.5 (a) Load Radius

Most current WTIVs cranes are able to lift about 1,200 tons but only at a load radius of about 10 meters. Since the crane will need to access OWT components over the entire deck, the useful load radius is about 300 tons at 40 meters. This is about the weight of current 5-8 MW wind turbines.

The load radius of future OWT in the 12-15 MW class will be requirement 500 tons at 40 meters. This corresponds to a crane with a maximum load of at least 2,000 tons. However, many vessels that are being built today have cranes specified to about 3,000 tons, to future proof and give more flexibility for lifting heavy foundations.

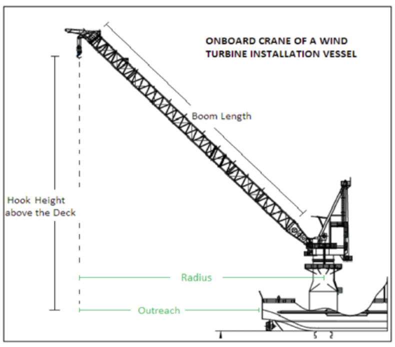

Figure 17 – Crane load radius nomenclature [5]

4.5 (b) Load Height

The other critical crane dimension is the load height. This is normally determined by the crane boom length, in the case of lifting from the deck. However, for a WTIV when lifting to sea level there are other factors such as leg length, water depth and the jacking height. The boom length has grown from 100 meters to over 150 meters for the next generation of WTIVs.

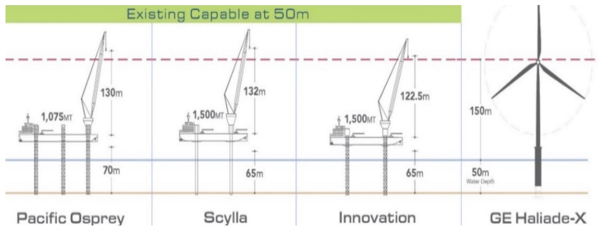

Figure 18 – Crane load height in 50m water [6]

For example, a WTIV crane may only be able to lift a tower piece 80 meters high off the deck, but it will be able to lift a nacelle onto the installed tower even though the tower is 95 meters above sea level. As OWT constructions methods have matured, installation of towers in a single lift is now the norm since it reduces deck space and installation time.

4.5 (c) Crane Installation

Where to locate the crane on the deck is another key design aspect. The crane must have good access to all the whole deck and be able to work within space restrictions created by the legs. It must also be possible to secure the long crane boom on a boom rest when the vessel is afloat.

Figure 19 – Leg work-around crane lifting 350t nacelle

Some common crane locations have been between the aft legs, in the vessel centre and directly next to a leg. As cranes have grown from a few hundred tons capacity to over 1,000 tons, the physical size of the cranes have grown to a point that the crane itself occupies a significant amount of the deck space. Therefore, it has now become the norm to have a work-around crane located around the aft starboard leg. It may seem that this location would place more load on the host leg, however a typical heavy load adds only about 2-3% over the static leg load. Also ballast water transfer can also be used to help balance leg loads during very heavy lift operations.

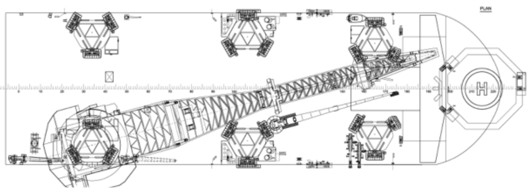

Figure 20 – Leg work-around crane deck layout [4]

The extreme crane boom lengths have created challenges in how to arrange the boom rest. One design is to have a complex tapered boom arrangement so that the boom will fit between the forward legs. Another solution is a parallel twin boom that will sit over the front leg. Although this simplifies the crane design and cost, the vessel must always jack-up before the boom can be luffed in or out of the boom rest.

5 FUTURE DEVELOPMENTS

5.1 TURBINE INSTALLATION VESSELS

It is clear that the development of the WTIVs is closely tied to the growth of OWTs. In addition to maturing construction methods, larger OWTs have been key in driving down the cost of offshore wind energy. With floating OWT still in its infancy, larger WTIVs are recognised as the only options for installing fixed bottom OWTs.

KNUD E. HANSEN has been active in developing these next generation of WTIVs for a number of leading European offshore construction companies. The following table compares some of the vessel principal particulars. These vessels have a newbuild cost of about 450 MUSD.

Operator	Jan De Nul	Van Oord	KEH
Name	Voltaire	-	Atlas C
Year in service	2022	2024	Concept
Length (LOA)	170 m	175 m	170 m
Moulded beam	60 m	-	60 m
Hull depth	14.6m	-	13.2m
Design draught	7.5m	-	6.5m
Cargo area	7,000 m^2	-	6,800 m^2
Jack deadweight	16,000 tons	-	18,000 tons
Crane max. load	3,000+ t	3,000+ t	3,000 t
Crane load height	163 m	-	160 m
Max. water depth	80 m	70+ m	80 m
Speed	11.5 kn	-	12.0 kn

Table 4 – Principal particulars of recent WTIV by KEH

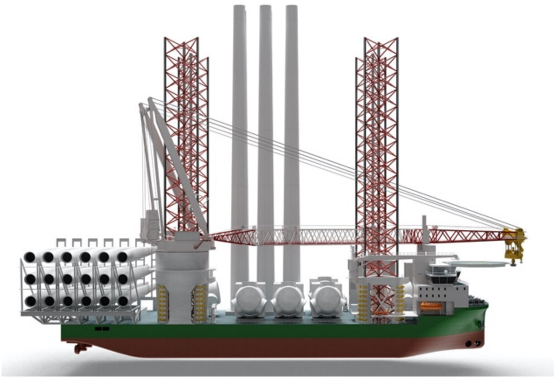

Figure 21 – Atlas C (KEH concept design)

5.2 OTHER CONSTRUCTION VESSELS

While self-sufficiency has continued to be fundamental to the WTIV concept, specialisation is increasing as offshore windfarms move into deeper water and construction methods mature. WTIV are highly complex and expensive vessels, whose hire time must be optimised to reduced construction costs.

As windfarms move into deeper water, the foundation type has changed to the gravity and jacket type that do not require the high level of handling precision for installation compared to the mono-pile type. Furthermore, the weight and size of these foundations are considerably more massive than the wind turbines they are supporting. Therefore, installation of foundations is changing to vessels with even larger cranes and greater deck space than WTIVs. However, despite being even larger than WTIVs, these vessels do not need expensive legs to jack-up.

Figure 22 – Heavy lift vessel for foundation installation (Jan De Nul)

In further specialisation, the WTIV only undertakes the physical erection tasks of the OWT on-site. Once construction is complete, the WTIV will move onto the next wind turbine installation. The final set-to-work and testing of each wind turbine is carried out by smaller and less expensive Commissioning Service Operation Vessels (CSOV) which may take a few days to complete.

5.3 DESIGN USING VIRTUAL REALITY

The concept 3D model of the vessel is being used by the client for various internal and external communication and promotion purposes where a realistic visual impression of the future vessel is needed. The model is also brought into ShipSpace™, a virtual reality design review and collaboration tool. This is particularly useful with the complex geometric relationship between the crane, legs and cargo on a WTIV.

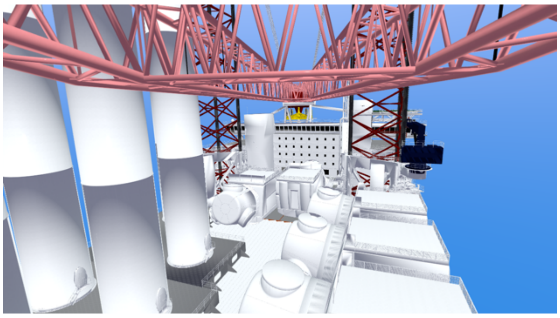

Figure 23 – VR review of WTIV crane operations (ShipSpace™)

The detailed model enables also the owner, crew and other stakeholders to review and comment on the vessel arrangement from a human factor engineering perspective. The ShipSpace™ system enables users to explore and investigate the entire vessel in virtual reality, which has proven to enable more accurate, thorough and much richer feedback from stakeholders and subject matter experts when compared to looking at drawings or pictures of the vessel. Users often comment that the convincing experience provided by the ShipSpace™ system is akin to being on board a real vessel.

As the basic design is finalised and detailed drawings and 3D models are received from the shipyard, ShipSpace™ is being used to verify that the final design elements will meet with the initial capabilities specified and also any operational concerns, such as accessibility to equipment for maintenance.

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7 LIST OF TABLES & FIGURES

8 AUTHORS BIOGRAPHY

Ken Goh holds the position of General Manager, at Knud E. Hansen Australia and specialises in mechanical engineering and advanced concepts in ship design. His project experience includes ferries, cargo, offshore, research, icebreakers and naval vessels. He is also active in the development of autonomous and wind powered vessels.