SENSE – Self Erecting Nacelle and Service System

General Description

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The SENSE System is a new integrated solution for transporting, installing and servicing principally offshore wind turbines. It allows the rotor nacelle assembly of the turbine to be installed and removed without the requirement for a large crane vessel and within short weather windows.

SENSE is particularly competitive where turbines are installed in deep waters and/or in locations far from shore. This matches the current growth in offshore wind development in many parts of the world which is increasingly moving towards both deeper water and further offshore.

This document provides a general description of the SENSE System, detailed descriptions of key aspects and the advantages of SENSE compared to current methods.

1. HOW IT WORKS

The SENSE System allows the installation and removal of the rotor nacelle assembly without the requirement for a large crane vessel; instead the pre-assembled and tested rotor nacelle assembly is transported and installed using less expensive and more widely available offshore support vessels.

SENSE resolves the issues of transferring a large load (the RNA) from the transport vessel to a substantially static platform (a fully erected tower) in a wide range of sea conditions and using the tower itself as the structure to hoist the RNA. The process is reversible for maintenance and replacement.
### 1.1 Installation
The description below sets out the main process steps of the wind turbine installation process.

<table>
<thead>
<tr>
<th><strong>Install multiple towers quickly and efficiently using a large crane vessel</strong></th>
<th><strong>Transfer the rotor nacelle assembly to the tower</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• A jack up or semi-sub is used to efficiently install towers.</td>
<td>• Once the rotor nacelle assembly is locked on to the tower the installation vessel detaches and moves away to install the second nacelle assembly.</td>
</tr>
<tr>
<td>• The weather window for this operation is less onerous than for a nacelle assembly. Install up to 4 per 24 h using jack up semi-sub crane vessel</td>
<td>• A power and control umbilical cable is plugged into the wind turbine power system and the rotor nacelle assembly raised up the tower.</td>
</tr>
<tr>
<td>• If winds are high the nacelle is raised safely away from the immediate spray zone and attached at the bottom of the tower.</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th><strong>Assemble the rotor nacelle assembly at the dockside</strong></th>
<th><strong>Climbing the tower</strong></th>
</tr>
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<tbody>
<tr>
<td>• The nacelle and rotor are assembled at the dockside with the rotor flat and the nacelle vertical.</td>
<td>• The multi-use transport carriage (fitted with lift motors and a control system) clamps to and climbs the ratchet rails fitted either to two adjacent legs or to the tapering cylindrical tower, with the blades lying horizontal, and the wheel base narrowing.</td>
</tr>
<tr>
<td>• Fit the transport carriage to the rotor assembly. This carriage is re-useable and fitted with the lift motors and a control system.</td>
<td>• The nacelle assembly is supported at its Centre of Gravity and locked vertical with a hydraulic ram fitted to the transportation unit, until it reaches the correct location at the top of tower for installation.</td>
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<tr>
<td>• A common interface arrangement allows the transport carriage to be connected to various turbine types.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Load-out the rotor nacelle assembly onto an installation vessel</strong></th>
<th><strong>Rotation at the top of the tower</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• The transportation and handling system is mounted to the deck of a standard construction vessel.</td>
<td>• At the top of the tower the nacelle assembly is rotated around the attachment pivot by a hydraulic ram.</td>
</tr>
<tr>
<td>• The WTG transport carriage interfaces with this transport and handling system.</td>
<td>• Once horizontal, the transport carriage gradually lowers the rotor nacelle assembly on to the top of the tower.</td>
</tr>
<tr>
<td>• Two or three nacelle assemblies can be transported on a typical construction vessel.</td>
<td>• The yaw bearing is rotated to align the bolt holes with the tower flange.</td>
</tr>
<tr>
<td>• Each rotor nacelle assembly slides on rails onto a handling system located on the vessel which consists of a rail system feeding the nacelle assembly to a heave compensated arm fitted with automated positional control to target and coordinate transfer to the tower rails.</td>
<td>• Once sufficient bolts are in place the transport carriage is disconnected and lowered to the bottom of the tower for collection.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Completion</strong></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>• The construction vessel returns to pick up the transport carriage and then goes back to port to collect further rotor nacelle assemblies</td>
<td></td>
</tr>
</tbody>
</table>
1.2 Heavy Maintainance

a) Nacelle Assembly exchange
The installation process is fully reversible allowing the complete rotor nacelle assembly to be removed and replaced quickly with a new/refurbished unit. It is anticipated that replacement will be completed in one operation, resulting in the shortest possible downtime. A Transport Carriage is fitted to the tower rails and raised up the tower to the defective nacelle assembly. The pivot pins and ram are re-attached, yaw ring connecting bolts are removed, the nacelle assembly is rotated back to the vertical position and lowered to the tower base for removal and replacement.

b) Major Component exchange
Alternatively, all major components can be exchanged using the Nacelle Service Platform or the Rotor Service Platform, or a combination of both. These platforms are transported to the turbine and engaged with the tower rail using the SENSE Vessel to Tower transfer system. The detail design of these platform will need to be optimised and maintenance procedures developed to suit the requirements of each wind turbine design.

Rotor Service Platform -
- Rotor and blade inspection and repair.
- Replacement of pitch bearings and blades.

Nacelle Service Platform -
- Generator replacement
- Gearbox
- Mainshaft and main bearings

2. COST SAVINGS
Research so far using conservative cost estimates show that the use of the SENSE System on at the baseline shallow water (30m) site will reduce the LCoE by a nominal 4% throughout the project life cycle. Refer to Attachment 2 for details. This cost benefit is expected to increase to 8% or higher as the design is refined; cost savings increase rapidly as they are assessed for a deep water
site (>60m) further away from land and with larger (10MW+) turbines.

2.1 CapEx savings

a) SENSE uses construction vessels for installation which are more readily available at competitive prices and can be mobilised at shorter notice compared to crane vessels. The concept easily scales to the projected 10 MW+ turbines (the market may not so quickly provide large crane vessels to keep pace with this development curve).

b) Conventional installation methods have flattened out to an average 24 hours per turbine with a jack up barge in attendance for construction onto the foundation. Using SENSE the RNA can be installed in parallel by multiple SENSE equipped vessels leading to a much shorter construction programme constrained only by the time required for the supply vessel to deliver and transfer the turbine to the tower estimated as <<2 hours; this creates a significant improvement in the overall project delivery.

c) This rapid installation rate significantly reduces the construction finance risk profile and significant interest cost of large wind farms now under development by generating early revenue.

d) Weather critical operations are shorter duration so can take advantage of narrow weather windows.

e) Only one short ‘lift’ operation is needed to transfer the rotor nacelle assembly onto the tower base rails which can be completed quickly with minimal vessel time on station.

f) The rotor nacelle assembly can remain at the base of the tower if necessary until a suitable weather window is available to continue raising it to the tower top.

2.2 OpEx savings

a) Large cranes are not needed for major component replacements, leading to lower refurbishment costs mid-life and lower OpEx costs in the later years of operation.

b) The ability to quickly exchange the complete rotor nacelle assembly could lead to cheaper wind turbines because it will allow a design philosophy with reduced design margins, less built in redundancy and no requirement for complex internal repair facilities on each turbine.

In the event of a major failure, rather replacing the individual major component the complete nacelle and rotor assembly is ‘swapped out’. In this way a turbine is back up and working in one ‘weather window’.

This aspect is a particular advantage for the following reasons –

- The risks of deploying advanced technology to further reduce costs can be more easily managed – e.g. serial faults or retrofits can be very expensive or impossible to rectify in-situ with conventional installation and service approaches.
- Although offshore wind turbines are becoming very reliable, there will continue to be early and unexpected failures of major components.
- Repairs to the defective unit are performed under factory conditions onshore leading to lower failure rates of repaired units.

c) During the operations phase, SENSE can be used for external inspections of the turbine, providing a secure platform for tower and blade inspection and repair.
d) a), b) and c) will reduce overall O&M costs and increase availability of the wind farm. The ‘least cost sweet spot’ will move closer to an availability of 97% which is the norm for onshore wind farm.

3. SAFETY

Although the SENSE System is a radical departure from current transport and installation techniques, the practicality and safety of these novel aspects have been established by comparison with existing technology.

Using SENSE the overall safety ranking will be improved compared to existing techniques because there are few individual lifting operations and by design, the vessel to tower transfer operation and hoisting the nacelle and rotor assembly up the tower are carried out under automated control with operators well away from the loads.

4. APPLICATIONS

The SENSE System can be used for the installation and servicing of any wind farm project, both on and offshore and in principle with any turbine type and foundation design, fixed or floating.

4.1 Offshore Wind

The SENSE System will be particularly competitive wherever offshore turbines are installed in deep waters, in locations far from shore or difficult seabed conditions. This competitive position matches the current growth in offshore wind development in many parts of the world, which is increasingly moving towards both deeper water and further offshore.

Floating foundations are quickly becoming a major part of the solution for exploiting distant and deeper locations. In some scenarios the SENSE System may not be needed for the initial turbine installation (if they are floated out completely assembled) but using it will reduce operational costs because -

a) It allows defective turbines to be repaired or exchanged without needing a semi-submersible crane vessel

b) Floating the complete unit back to shore for major repair is very costly both in direct cost and turbine downtime.

<table>
<thead>
<tr>
<th>Semi-submersible floating foundation</th>
<th>Using the SENSE System allows –</th>
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<tbody>
<tr>
<td></td>
<td>• The foundation to be permanently deployment, so eliminating the need to disconnect anchors and incorporate and maintain ballast systems.</td>
</tr>
<tr>
<td></td>
<td>• The ‘platform’ created by the semi-sub structure to be used as a work space onto which the rotor nacelle assembly can be lowered to carry out repair work.</td>
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</tbody>
</table>
4.2 Onshore Wind

SENSE will be competitive for onshore locations where the nacelle rotor assembly needs to be removed regularly or where large cranes are not easily available or very expensive.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Why SENSE is Better</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use and improve existing installation processes and vessel concepts.</td>
<td>Installation systems and concepts continue to be improved in small steps, but the rate of improvement, and therefore the potential for cost reduction is slowing down as the concept of using a jack-up crane vessel reaches its lowest cost base. Existing installation systems and vessels will continue to be competitive and be used for near shore shallow water but are become less competitive and in some cases impractical or prohibitively expensive for use further from shore and in water depths greater than 70m. SENSE also opens up other areas of cost reduction and improvement – for example, a re-evaluation of the cost/benefit of sophisticated (and expensive) monitoring, in situ repair schemes and levels of system redundancy. When (not if) a major failure does occur then a full repair carried out onshore following complete removal of the nacelle assembly will be safer, quicker and far more reliable than the same repair undertaken offshore.</td>
</tr>
</tbody>
</table>

4.3 Using SENSE on existing operational turbines

Preliminary engineering and design work has confirmed the feasibility of retro fitting the SENSE rail system to the outside of the tower using normal O&M maintenance equipment and procedures. Recertification of the towers will be required to allow this modification but this is not considered to be a problem in principle.

This arrangement will allow heavy maintenance to be carried out on all of the major components (except for the yaw bearing) but it will not be possible to exchange the rotor nacelle assembly as a single unit.

5. ADVANTAGES OF SENSE (COMPARED TO ALTERNATIVES)
### Blade and tower repairs and inspections

Insitu blade and tower repairs and inspection are extremely difficult and hazardous.

SENSE towers have a set of rails running up the tower which are used for the ‘self installing’ operation for the nacelle assembly. When the turbine is in operation these rails can be used to support a mobile platform, provides a stable working area to undertake work safely and during a far wider weather window than is possible using suspended platforms.

It is possible that this platform could be utilised to replace a single blade.

### Similar concept for installation without a jack up

The left illustration is from an installation concept proposed by a German university 2014. It does not use a crane vessel but it does require a jack up barge and therefore has similar limitations to existing methods.

Tipping the nacelle and raising the nacelle rotor assembly up the tower was used by a number of large onshore two bladed turbine designs in the 1980’s and 1990’s when large cranes were not so readily (and cheaply) available.

These examples demonstrate that some aspects of the SENSE concept are being or have been considered, and so should provide confidence that it is a practical option. The advantages of the SENSE over these alternatives is that it is a fully integrated transport and installation system for offshore turbines and is capable of being deployed in any depth of water – and therefore suitable for all future projects.

### Completely assemble the turbine with tower onshore

Examples are -
- RePower 5M / Svannen Heavy Lift Vessel
- W3G Marine presented a design for a specialist multi-purpose installation crane vessel capable of undertaking all aspects of piling, jacket installation and fully assembled turbine installation.
- Huisman Wind Turbine Shuttle (left)

This concept has appeal because the turbine can be fully assembled and commissioned onshore. It is considered far more vulnerable to weather and will be slower for installation. It will be slow and costly to use for ongoing operations (removal and re-installation following major failures) so far less flexible than SENSE.

### Use floating foundations for deep water

Floating foundations solve the deep sea deployment problem, but ‘floating them back’ for major servicing is a disadvantage because of the time out of production and the major facilities required on shore. Permanently fixing them eliminates the cost and upkeep of disconnecting anchor and ballast systems and transport back to shore.

SENSE can be used to complement the advantages of floating foundations and help to reduce some of their dis-advantages –
- Semi-submersible floating foundation - The ‘platform’ created by the semi-sub structure could be configured to be used as a work area, with the rotor nacelle assembly lowered down the tower (but remaining attached to the tower) whilst repairs are completed.
- Floating Spar buoy - A deep water harbour will not be needed for initial installation or to undertake servicing.
- Tension Leg Platforms (TLP) have significant benefits over a floating platform such as reduced material requirements and smaller seabed footprint, but untethering a TLP to float it back to port for service is particularly difficult. SENSE will help to increase the wider use of TLP and gain these advantages.

### 6. DETAILED DESCRIPTION OF KEY ASPECTS

#### 6.1 Transport of RNA

The design of the transport system has been based upon an offshore construction vessel similar in size and characteristics to the North Sea Giant. This vessel would be capable of transporting and installing two RNA per trip. Stern and side offloading arrangements are under consideration.
6.2 Vessel to Tower Transfer

Option 1 – Active Compensator Platform

This option is a development of the principles employed on existing technology (e.g. Bargemaster platform) but with additional functionality and control systems under development with ISC Ltd allowing much higher loads to be transferred and achieving a level of control setting the delivery platform substantially motionless relative to the delivery point on the tower.

Option 2 – Passive Compensator Platform

This option uses gravity and inertia to achieve the same objective of setting the delivery platform substantially motionless relative to the delivery point on the tower. This Option has advantages in simplicity and lower power requirement: it is subject to ongoing patent drafting and filing and details cannot yet be presented.
### 6.3 Transferring the RNA up the tower

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Typical drawing/diagram</th>
</tr>
</thead>
</table>
| 1.   | **General description of the Transport Carriage**  
The Transport Carriage is assembled onto the completed nacelle and rotor assembly at the dockside. It consists of the following main elements—  
a) Structural framework to support nacelle  
b) Sliding bearing assembly and clamping system to engage with the tower rails  
c) Pivot mounting to interface with the nacelle with removable pivot pins  
d) (Power pack/electrical connection)* drive motors and drive wheels to allow self propulsion in moving the entire assembly from delivery ship to Tower  
e) Actuator assembly connecting and controlling the hub relative to the structural frame  
f) Umbilical power and control cable.  
g) Control system  
h) The power arrangement can be either hydraulic, powering hydraulic motors and hydraulic ram, or fully electrical driving geared electric motors and a linear electric actuator. | ![Typical drawing/diagram](image.png) |
| 2.   | **Transport Carriage attachment to rotor nacelle assembly**  
The Transport Carriage attaches to the nacelle assembly via the two pivots on the underside of the nacelle assembly and which are located close to the nacelle assembly Cof G. The Transport Carriage is oriented relative the nacelle assembly but the extension of the hydraulic ram.  
During nacelle assembly and initial transportation the Transport Carriage is hydraulically locked in the horizontal orientation and no power is applied to the Transport Carriage systems.  
When the vessel is close to the tower the carriage is powered from the vessel as it transports to the launch area it and when it is ready to offload the Transport Carriage is oriented vertically.  
It is then transported across to the tower and positioned to allow engagement with hooks (or similar), the tower guide rails and driving mechanism.  
An umbilical power cable is attached and powered up from the grid connection at the tower (or via temporary power). Control of the Transport Carriage functions (orientation, drive motors) is a combination of automatic and manual intervention control via a remote control console. | ![Typical drawing/diagram](image.png) |
### 3. Pivot point at the Centre of Gravity (approx).

The figure shows a typical nacelle layout of a large wind turbine. There are some variations to this layout but all are sufficiently similar that the general principle described here applies.

With the rotor (hub and blades) assembled and attached to the nacelle drive train (gearbox, generator and associated nacelle electrical equipment) the CofG in the horizontal plane of the complete assembly will fall somewhere between the hub connecting flange plate and the front edge of the tower. A support pivot will be provided at this point to minimize the stress and effort required to rotate the entire assembly from the vertical to horizontal, and to minimize the moment of the mass about the pivot during transit.

The hinge points on the nacelle can either be an integral part of the nacelle, or alternatively and 'adaptor plate' will be provided which bolts between the yaw bearing and the tower top. The adaptor plate design can be modified to suit the exact position of the CofG for each turbine.

By pivoting the nacelle about its C of G the forces required to rotate the nacelle are minimised and more easily controlled.

### 4. Transport Carriage engagement the track on the tower

The diagram shows a possible implementation of a rail track arrangement consisting of two ‘T’ sections attached to the tower and which incorporate features to allow a rack and pinion drive arrangement. Transport Carriage structure hooks behind the ‘T’ sections and incorporates sliding bearings to guide the Transport Carriage up the tower.

a) For a conventional tapered tubular tower, the guide rails are set the same distance apart over the full length of the tower. Three sets of guide rails are provided 120 degrees apart around the tower. This allows a choice of positioning of the vessel relative to the tower to suit weather conditions and provides structural symmetry. The slots between each section of the guide rail are tilted slightly inwards to keep the carriage centred between the rails.

b) For a 3 legged lattice tower, two ‘T’ guide rails would be attached to each leg such that (similar to the tubular tower) it allows a choice of positioning of the vessel relative to the tower to suit weather conditions. Because the tower legs taper, the design of the Transport Carriage provides sliding axles to allow for the narrowing of the distance between the main legs with elevation. The slots between each section of the guide rail are again tilted slightly inwards to keep the carriage centred between the rails and the sliding axles sprung loaded to avoid eccentricity of the carriage assembly.
5. **Raising the rotor nacelle assembly to the top of the tower**

Once the Transport Carriage is fully engaged with the tower rails, power is applied to the lift motors to hoist the nacelle assembly up the tower. At a mechanically defined location at the top of the tower an hydraulic ram operating on the outward end of the hub controls the rotation of the nacelle to engage precisely on the yaw ring bottom flange on the tower, and the connection bolted down securely.

**Transport Carriage release mechanism**

Once the nacelle assembly has been secured to the tower top, the pivot pins connecting the Transport Carriage to the nacelle assembly are removed (either by powered actuators or as a manual task). There is no load on these pivots at this stage. The hydraulic ram is also disconnected from the hub.

The Transport Carriage can now be lowered to the base of the tower for collection.