Offshore Wind Programme Board

Lightweight Offshore Substation Designs

**Final Summary Report** 

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## ABBREVIATIONS USED

Initials	Definition
СТ	Current Transformer
DC	Direct Current
DFF	Design Fatigue Factor
DP2	Dynamic Positioning (with Class 2 redundancy)
DTS	Distributed Temperature Sensor
EPCI	Engineer, Procure, Construct, Install
EWEA	European Wind Energy Association
FEED	Front End Engineering Design
FID	Final Investment Decision
GIS	Gas Insulated Switchgear
HAZID	HAZard IDentification study
kV	Kilo Volt
kVA	Kilo Volt-Ampere
kW	Kilo Watt
MV	Medium Voltage (i.e. 33kV or 66kV)
MVA	Mega Volt Ampere
MVAr	Mega Volt Ampere Reactive
MW	Megawatt
OFTO	Offshore Transmission owner
0&M	Operations & Maintenance
ONAN	Oil Natural Air Natural (transformer cooling)
OTM	Offshore Transformer Module
OWPB	Offshore Wind Programme Board
RAM	Reliability, Availability and Maintainability
SCADA	Supervisory Control and Data Acquisition
SQSS	Security and Quality of Supply Standards
TRS	Tender Revenue Stream
VT	Voltage Transformer
WTG	Wind Turbine Generator

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#### 1 SUMMARY & CONCLUSIONS

This report describes the concept of a "lightweight" offshore substation, and in particular it describes one implementation of the concept: the Offshore Transformer Module (OTM) which has been developed by Siemens.

The OTM concept exists in different versions:

- i) it can be "standalone" (the OTM occupies its own substructure) or "integrated" (the OTM shares a substructure with a wind turbine);
- ii) it can incorporate a shunt reactor where necessary (e.g. due to very long export cables);
- iii) the substructure can be a jacket, a monopile, or in principle an adapted form of any substructure suitable for a 7-8MW wind turbine;
- iv) various "optional extras" such as lifting frames, louvered walls around the transformer, or larger platform cranes can be incorporated without affecting the main design of the OTM.

The "base design cases" that have received the bulk of the design work are the standalone and integrated versions of the OTM, without reactors or optional extras, on four-legged jacket substructures. Siemens has undertaken considerable development work on these base designs: they note that their development work has "spanned 130 technical deliverables and 12 months of design work using real project site conditions". Notice to proceed with construction of the first OTMs is expected within less than 12 months.

Siemens's desire is to put extra effort into optimising these base case designs, and then to adapt these base designs to yield the designs for future projects rather than designing the new projects from a clean sheet; they refer to this as a "adopting a product mentality". The authors of this report agree that this approach should allow reductions in design time, cost and risk on future projects.

The report concludes that:

- The OTM concept can be expected to reduce costs by £1.7/MWhr (in 2015 prices). This figure is based on the integrated OTM design. It would be about a third less for the standalone design, while a higher value is likely if the OTM were to be applied alongside an array design that had been optimised for OTMs.
- ii) The OTM appears well engineered, and although it includes several measures new to the UK wind industry in order to reduce cost and weight, these appear to have been applied with suitable consideration given to the need to ensure safety, reliability, availability and maintainability. Our conclusions on these issues are summarised in table 1 below.

- iii) The standalone base design is ready for immediate commitment by developers (i.e. developers selecting this concept can be confident that it is feasible and will provide significant cost savings).
- iv) The integrated base design is also ready for immediate commitment, although developers will first need to confirm that they are comfortable with the additional contractual interfaces.
- v) The level of readiness for various OTM versions is set out in Table 2 below.
- vi) Siemens is not the only company currently investigating the potential of lightweight single-transformer substations, and the concept could also be applied by other manufacturers or by developers who chose to engineer their offshore substations in-house.
- vii) ORE Catapult has recently undertaken a study of the accelerations experienced at the tower-base level of a wind turbine and their acceptability to high-voltage equipment. While this particular study is rather basic and only covers one scenario, it may provide insight into the scope of a more comprehensive study that would be able to alleviate current concerns that substation equipment could suffer long-term wear due to the increased accelerations imposed by sharing a substructure with a wind turbine.
- viii) Further work by OWPB is recommended to investigate the potential for increased cost savings by optimising the array cabling for the characteristics of lightweight substations. The authors also encourage Siemens to undertake further work refining versions of the OTM that include a shunt reactor and that use monopile substructures.

lssue	Mitigation / Authors' Commentary
Fire protection	DNV has agreed compliance with DNV-OS-J201 (subject to final study at detailed design stage). Furthermore the OTM has better fire protection than several UK offshore substations already in service with OFTOs.
HAZID study for standalone OTM	HAZID concluded that risks are similar or less than on conventional substations
HAZID study for integrated OTM	HAZID identified potential risks from objects dropped from turbine onto OTM, from ice dropped from turbine onto OTM, and from a fire on the OTM when personnel are in the turbine.
	Mitigating measure were identified for all of these risks and Siemens and the developer were confident that these could have been successfully applied.
Fault on an OTM's single transformer	The size of UK wind farms is such that all would be expected to have at least two OTMs. This report assumes throughout that these multiple OTMs would be connected by cables so that, should a transformer fail, power can be rerouted

Table 1: Summary of Conclusions in relation to Safety, Reliability, Availability and Maintainability

	through the transformer in another OTM.
	Sufficient OTM-to-OTM cables to give a level of resilience against transformer faults fully equivalent to a conventional two-transformer offshore substation are included in the £1.7/MWhr OTM benefit figure (see section 8).
Synthetic ester: limited track record at ≥220kV	Following tests on a sample simulating a 400/132kV transformer, National Grid now accepts synthetic ester cooled transformers at 400kV. The first such transformers have been manufactured by Siemens and are to enter service in late 2015. This risk therefore appears to be acceptable.
No helideck	A heli-hoist area is provided. Helidecks are unusual on UK offshore substations. Studies by TenneT for their forthcoming Dutch offshore substations indicated that the additional cost of a helideck can not be justified. Siemens's decision not to provide a helideck is, therefore, reasonable.
Limited platform crane capacity	Siemens has yet to determine the specification for the base-design OTM's platform crane. It is therefore possible that the crane will have insufficient capacity to lift some of the heavier spare parts (e.g. auxiliary transformer, 220kV VT) which can be lifted on most conventional substations. Siemens have confirmed that if the platform crane chosen for the base design is judged inadequate by customers then they can provide an uprated crane as an option.
Space for maintenance & repairs	Siemens has confirmed that the clearance around all electrical equipment on the OTM meets all of their own "manufacturer's recommendations" for onshore installations.
OFTO/Generator segregation	OFTO-owned and generator-owned equipment is not in separate rooms, but is in separately lockable cabinets. This is considered acceptable. The base design provides a single substation control system for generator and OFTO owned assate. Signaps have confirmed that if this not acceptable to
	customers then there is sufficient panel space to allow separate substation control systems for the generator and OFTO to be fitted.
Corrosion	All OTM transformer coolers can be replaced without de-energising the transformer and without needing external cranes or any boat larger than a crew transfer vessel. This is better than most conventional substations.
No diesel for emergency power	This report assumes throughout that UK wind farms will have multiple OTMs and OTM-to-OTM cables. These links to the other OTM(s) in the wind farm mean that emergency power on an OTM should be more reliable than on a conventional substation with a single export cable and a diesel. Siemens's approach is therefore considered acceptable.
Cable Pull-in	Siemens have undertaken detailed planning and storyboarding.
Design Fatigue Factor on integrated OTM	On the integrated OTM the DFF is reduced from the value of 10 specified in DNV-OS-J201 to a value of 6. Siemens has agreed this with DNV, and it is expected that DNV would certify an integrated OTM on this basis.

## Table 2: Readiness of OTM Concept

Variant	Readiness
Standalone OTM on a jacket substructure	Ready for immediate commitment by developers.
(One of the Base Design Cases)	
Integrated OTM with a wind turbine sharing jacket substructure	Ready for immediate commitment by developers. Note that for some developers this option may require the
(One of the Base Design Cases)	acceptance of additional contractual interfaces.
Standalone OTM on tripod or gravity base substructure	Ready for immediate commitment by developers.
Standalone OTM on monopile	<ul> <li>Ready for commitment by developers subject to:</li> <li>checking that the movement amplitudes and frequencies that would be experienced when using a monopile adapted from one intended for wind turbine service are acceptable for high voltage equipment, and</li> <li>checking how the required number of cable J-tubes will be accommodated.</li> </ul>
OTM with a Shunt Reactor	Ready for immediate commitment by developers. (Although Siemens have not completed design work on an OTM with a shunt reactor, they are confident of the feasibility of this version. A proof-of-concept check by the authors – see section 7.6 – tends to confirm Siemens's position).
OTM sharing a monopile substructure with a wind turbine ("integrated")	In addition to the studies described above for a standalone OTM on a monopile, the authors recommend an additional study to investigate whether long-term cyclic acceleration levels could be materially increased by the presence of the turbine, and – if so – whether this would be acceptable for high voltage equipment.
Standalone OTM equivalent by non-Siemens vendor.	There appears to be no reason why other vendors cannot provide lightweight substations with the same specifications as the OTM. However the FEED process already completed by Siemens for their base designs would need to be repeated by other vendors.
Integrated OTM equivalent by non-Siemens vendor.	Siemens has applied for a patent covering aspects of their integrated OTM base design. It is beyond the scope of this report to comment on the likelihood of this patent being granted or the consequences if it is. The authors have not been able to locate the text of the patent application.

#### 2 INTRODUCTION AND BACKGROUND

The increase in the capacity of offshore wind turbines – from no more than 3MW ten years ago to as much as 8MW today – has been accompanied by an increase in the capability of the heavy lift vessels used for their installation. Over this period, however, offshore substations have also increased in weight so that the installation of offshore substation topsides or substructures in a single lift continues to be beyond the capability of the cranes used for wind turbines. Instead it requires the use of larger specialist heavy lift vessels or multiple lifts by turbine installation vessels.

This report describes an alternative approach to the design of offshore substations, where the topsides are sufficiently lightweight that they can be installed by a turbine installation vessel<sup>1</sup> in a single lift.

In order to learn more about this approach, the Grid Group of the Offshore Wind Programme Board<sup>2</sup> (OWPB) wrote to the main suppliers of substation equipment and turnkey substations in the UK. We received responses from three companies setting out their views on lightweight offshore substations. One of the respondents, Siemens, additionally invited persons acting on behalf of the OWPB to visit its offices in order to examine their implementation of the lightweight offshore substation concept in some detail.

Siemens refers to its implementation of the lightweight concept as an Offshore Transformer Module (OTM). The current status of the OTM concept is that:

- i) Siemens have completed 12 months of design work on the OTM concept, work which has involved "130 technical deliverables". This development work has been based on specific "real world" sites.
- ii) Based on this work Siemens have produced two "base design case" versions of the OTM. The authors found that almost all design decisions for these versions had been made, and for the few exceptions Siemens had a clear view of requirements and expected to finalise the designs in the next few months.
- iii) Two UK wind farm projects have publicly announced that they will be using the OTM: Beatrice<sup>3</sup> and Neart na Gaoithe<sup>4</sup>. The authors understand that both projects expect to reach their final investment decision in 2016.
- iv) For future projects Siemens's ambition is to take the versions of the OTM they have already designed, and to adapt them to new requirements. This contrasts with the previous norm where detailed and varying user requirements led to quite radical differences even between two offshore substations designed by the same vendor. Siemens refers to the approach it hopes to follow in future as a "product mentality"

<sup>&</sup>lt;sup>1</sup> Or the vessel used for the installation of the wind turbine's substructure, if this is different.

<sup>&</sup>lt;sup>2</sup> A joint initiative of the UK offshore wind industry and the UK authorities aimed at reducing the cost (including transmission costs) of offshore wind to £100/MWhr by 2020.

<sup>&</sup>lt;sup>3</sup> See the Draft Offshore Decommissioning Programme and the September 2015 Project Update, both on the SSE website.

<sup>&</sup>lt;sup>4</sup> See Mainstream Renewable Power press release of 13 April 2015.

(i.e. where a standard product is adapted for the needs of a particular project), as opposed to the traditional "project mentality" where every offshore substation would have either been entirely bespoke or would have used a standard design unique to a single developer.

This report:

- i) Describes the features of lightweight offshore substations in general, and the Siemens OTM in particular.
- ii) Sets out the work undertaken by Siemens and others to identify and address concerns in relation to the innovative features of the OTM.
- iii) Describes and analyses the cost reduction potential of the OTM concept.

To assist in the preparation of this report Siemens provided access to confidential information concerning the OTM. This report has been written so that it contains only public domain information and information whose release has been authorised by Siemens; relevant confidential information placed in confidential appendices which are referred to at various points. Access to these confidential appendices is available to all wind farm project developers on signature of a confidentiality agreement with Siemens.

Other than deciding what information must be placed in these confidential appendices, and commenting on factual issues, Siemens has had no role in the writing of this report. The report has been produced by two organisations, both of which are completely independent of Siemens, and both of which are active within the OWPB:

- i) Transmission Excellence (TX). TX is a specialist in power transmission, with a particular focus on developing innovative solutions and cost reduction. TX was the primary author for the report other than Section 7.
- ii) Offshore Renewable Energy Catapult (ORE Catapult). ORE Catapult is the UK's flagship technology, innovation and research centre for offshore renewables. It combines research, demonstration and testing facilities with leadership, industrial reach and engineering expertise to help accelerate the design, deployment and commercialisation of offshore renewable energy technologies. ORE Catapult was the primary author for Section 7.

The report has been commissioned by the Grid Group of the Offshore Wind Programme Board (OWPB), and has benefited from discussions among the members of the group. However, the OWPB Grid Group accepts no responsibility for the accuracy and completeness of the report. The reader's attention is also drawn to the Disclaimer on page 2 of this report.

#### 3 LIGHTWEIGHT OFFSHORE SUBSTATIONS

#### 3.1 Definition

For the purposes of this report a lightweight offshore substation is defined as as follows:

A lightweight offshore substation is an offshore substation that can be installed by a vessel with a lift capability of 1000t, with the topsides being installed in a single lift.

The definition's requirement for a single topsides lift has been set because a single-lift approach will minimise offshore hook-up work with consequent cost savings. It is also noted that the multiple-lift approach has generally been avoided by offshore substations<sup>5</sup>, and that topsides that require multiple lifts are likely to be so heavy that the platform substructure<sup>6</sup> will need to be custom designed rather than being a derivative of the wind turbine substructures.

The 1000t lift weight is intended to provide a reasonable probability of reducing heavy lift costs from the high levels currently encountered in offshore substation installation to the lower costs seen for wind turbine installation. To do this the substation must be light enough that installing it using the same installation vessel(s) as the wind turbines and their substructures will not materially restrict the range of vessels competing to undertake the work. Therefore a lightweight substation topsides should weigh less than the lift capability of the smallest vessels generally used to install 7-8MW turbines and substructures. The method used to determine that 1000t was an appropriate limit is set out below.

Table 3 below has been derived by taking a full list of heavy lift vessels<sup>7</sup> and then removing those that are not used for the installation of wind turbines/substructures, those whose lift capacities are in excess of 1500t (i.e. oversized for wind turbine installation<sup>8</sup>), and those whose lift capacities are below 810t (i.e. too small to install 7-8MW turbines<sup>9</sup>). This gives the following "marketplace" of vessels:

<sup>&</sup>lt;sup>5</sup> A few examples of multiple-lift substations do exist, for instance on Humber Gateway and Horns Rev 2.

<sup>&</sup>lt;sup>6</sup> The term "substructure" will be used throughout this report to refer to the structure underneath the wind turbine tower and/or substation topsides. "foundations" are the part of the substructure below seabed level.

<sup>&</sup>lt;sup>7</sup> Source: 4Coffshore website

<sup>&</sup>lt;sup>8</sup> A number of very high lift capacity vessels have been used for turbine substructure installation. When used in this role, however, they generally charge lower rates – rates set by competition from mainstream wind installation vessels. For offshore substation work, which requires more of these vessels' capacity, much higher rates are charged. The capacities of these vessels are not, therefore, relevant to calculating an appropriate maximum weight for lightweight substations.

<sup>&</sup>lt;sup>9</sup> Future projects using large turbines in the 7-8MW class are likely to require this lift capacity at the very minimum: it is noted that the Westermost Rough project, which installed 6MW machines in modest water depths (<25m), still involved lifts of up to 810t for the monopiles (source: GeoSea). Future projects are likely to require even larger lifts.</p>

Vessel	Owner	Lift Capacity
Innovation	GeoSea	1500t
Scylla	Seajacks	1500t
Vidar	Jan de Nul	1200t
Pacific Orca	Swire	1200t
Pacific Osprey	Swire	1200t
Seafox 5	Seafox	1200t
Enterprise	MPI	1000t
Discovery	MPI	1000t
Adventure	MPI	1000t
Aelos	Van Oord	1000t
Sea Challenger	A2Sea	900t

Table 2. installation	vossols rolova	nt to octablichi	ing a definition	of "lightwoight'
Table 3: Installation	vessels releva	int to establish	ing a definition	or lightweight

Out of the "marketplace" of 11 vessels listed above, only one has a lift capacity of less than 1000t. This suggests that it should be possible to install a lightweight substation that requires no more than 1000t of lifting capacity at a cost comparable to wind turbine installation.

In practice a 1000t nominal lifting capacity doesn't mean that a topsides weighing 1000t can be lifted. Firstly, the weight of spreader bars, slings and other equipment associated with the lifting process must be deducted. And secondly crane capacity will be reduced when the object being lifted is more than a certain distance (typically 25-32m) away from the centre of the crane. Even though lightweight substations tend to be quite compact, they are still likely to be sufficiently large that some reduction in crane capacity results. The combination of these factors is expected to reduce the practical maximum weight can be lifted. It has been assumed by the authors, based on an initial review of published information, that all of the cranes with notional capacities of 1000t and higher should be able to lift a substation topside with a weight of up to 850t.

## 3.2 Comparison with "Traditional" Offshore Substations

Table 4 below shows the topsides weights for a selection of recent offshore substations. Nearly all of these substations have two transformers (exceptions are Northwind with one and Horns Rev 3 with three). As can be seen, none of these substations meet the definition of "lightweight" given above.

Project (installation date)	Source website	Substation capacity (MW)	Substation topsides weight (tonnes)	Power density (kW/t)
Northwind (2013)	ISC	216MW	1140t	190
West of Duddon Sands (2013)	ISC	389MW	1580t	250
Borkum Riffgrund (2013)	ISC	320MW	1880t	170
Humber Gateway (2014)	lemants	219MW	1140t	190
Dan Tysk (2013)	Strukton	288MW	3200t	90
Northsee Ost (2014)	ISC	295MW	1600t	180
Amrumbank West (2014)	lemants	288MW	2160t	130
Meerwind (2014)	SHL	288MW	3300t	90
Westermost Rough (2014)	STX	210MW	1500t	140
Gode Wind (2015)	ISC	582MW	2 x 1950t	150
Dudgeon (2016)	SLP	402MW	1800t	220
Horns Rev 3 (2016)	HSM	400MW	1800t	220
Sandbank (2016)	Bladt	288MW	2000t	140
Wikinger (2016)	Iberdrola	350MW	4800t	70
Nordsee One (2016-17)	Nordsee One	332MW	2200t	150
Rampion (2017)	E.on	400MW	1200t	330
Burbo, Race Bank, Walney extension (2016-18)	SPT	Up to 330MW	Up to 2500t	130

#### Table 4: recent offshore substations - topsides weights<sup>10</sup>

#### 3.3 Implications of a Lightweight Design

The goal of designing an offshore substation so that it can be installed by a vessel with a 1000t lift capacity has implications for many aspects of the design, both technical and contractual. In particular:

<sup>&</sup>lt;sup>10</sup> This is not a full listing of all substations installed or to be installed in 2013-17, rather it reflects projects for which weight information was found on public websites. "Self-installing" substations and DC converter stations are excluded. Note that German substations tend to be heavier than those seen elsewhere: this is likely to reflect the fact that in Germany offshore substations often contain substantial diesel generation and may act as maintenance bases for the wind farm.

- i) Transformer weight per MW tends to fall<sup>11</sup> as the size of transformer increases. This means that, in order to accommodate the most power on a weight-limited platform, a single large transformer will be better than two smaller transformers. Using a single transformer, however, will mean that the risk of curtailing energy exports from the wind farm will be higher unless suitable countermeasures are taken.
- ii) Accommodating a reasonable amount of power subject to a weight constraint is likely to drive designers to eliminate non-essential features. Examples are helipads, backup diesels, large platform cranes and segregated wind farm and OFTO rooms. Eliminating such features reduces costs as well as weight, but designers need to ensure that the safety, reliability, availability and maintainability of the platform is not materially affected.
- iii) Designing a substation to a weight constraint may need more time so that the structural design can be properly optimised: there is anecdotal evidence that in many cases additional weight and cost has been added to platform designs because of insufficient time for design optimisation. This could be addressed by extending the time and funding for front end engineering design, but a better approach might be to introduce a degree of standardisation so that new platforms are designed by adapting a reference design (which has been already been thoroughly optimised) rather than being designed from scratch.
- iv) A lightweight substation's topsides can generally be mounted on the same type of substructure as is used by the wind farm's turbines, with some minor modifications such as strengthening braces and additional J-tubes. Manufacturing and installing the substation substructure as part of the same large-scale operation as the wind turbine substructures should give significant economies of scale.
- v) Because much of the benefit of lightweight substations comes through their use of the same installation vessel as the wind turbines, and essentially the same substructures as the wind turbines, it is more difficult to have a full "turnkey" offshore substation contract<sup>12</sup> with lightweight substation concepts. A more economic arrangement is likely to involve restricting the substation contract to the electrical equipment, topside design and topside fabrication, with the substructure fabrication work being covered by an extension of the wind turbine substructure fabrication contract, and with topsides and substructure installation being covered by an extension of the wind turbine installation contract. Further economies may be gained by sharing subcontractors: for instance, the same structural designer and/or the same fabrication yard could be used for the substation topsides and the turbine substructures<sup>13</sup>.

<sup>&</sup>lt;sup>11</sup> Strictly speaking weight per MVA. In theory the weight of a transformer is proportional to its MVA rating raised to the power of 0.75. This means that as MVA increases the weight will increase more slowly and weight per MVA will tend to fall.

<sup>&</sup>lt;sup>12</sup>Where a single contract covers electrical equipment, topsides design, topsides fabrication, topsides installation, substructure design, substructure fabrication, and substructure installation

<sup>&</sup>lt;sup>13</sup> We understand that Siemens has been trying to apply this principle on its OTM projects.

- vi) Even if full turnkey substation contracts need to be abandoned, however, it should be noted that the total number of contractors on the wind farm project will not increase: it is simply a matter of transferring work to different contracts. Furthermore for the many offshore substations that are built using a multi-contract approach the lightweight substation concept would mean an actual reduction in the total number of contracts as the special substation installation contract and substation substructure fabrication contracts can be dropped.
- vii) Wind turbine substructures are sized primarily to deal with the dynamic forces from the wind on the turbine blades. Substations, in contrast, give rise to a static (weight) force. Because of the different types of force involved it is generally the case that a wind turbine substructure can support the forces from *both* a turbine *and* a lightweight substation topside with very little strengthening. Having both a substation and a wind turbine sharing the same substructure reduces project cost by eliminating the supply and installation of a substructure, by avoiding the need to lay submarine cables to the co-located turbine, and through the sharing of turbine and substation facilities.

#### 3.4 Lightweight Substation Implementations

The authors are aware of three companies that are exploring the potential of lightweight substations. These are:

- i) ABB, who presented the paper "Technical and Economic Evaluation of Distributed AC Power Collection for Offshore Wind Power Plants" at the 13<sup>th</sup> Wind Integration Workshop (Berlin, November 2014). This described a substation (see figure 1) that comprises a single 175MVA 220/66kV<sup>14</sup> transformer, three bays of 66kV switchgear and three bays of 220kV gear. This substation was to share a modified wind turbine substructure with a 6MW-class wind turbine. No information was provided on weights or auxiliary equipment.
- ii) DONG, who presented the paper "Distributed Substation: A Cost-Efficient Multi-Platform Topology" at the EWEA Offshore Wind Conference (Copenhagen, March 2015). This describes a substation (see figure 2) comprising a single 200MVA 220/33kV<sup>15</sup> transformer, a 90Mvar 220kV shunt reactor, and 220kV and 33kV switchgear. Topsides weight is slightly less than 1000t and substructures are to be based on the design used by the wind farm's turbines. The substructure is not shared with a wind turbine and the substation retains many of the features of conventional offshore substations such as relatively large cranes and a backup diesel to provide an emergency supply to the platform.
- iii) Siemens, whose "Offshore Transformer Module" (OTM) concept is discussed in more detail in the remainder of this report. Siemens' work appears to be much more advanced than that of either DONG or ABB, with detailed design work

<sup>&</sup>lt;sup>14</sup> The paper refers to 72kV, but presumably this is a reference to the maximum continuous voltage of a cable with a nominal 66kV voltage.

<sup>&</sup>lt;sup>15</sup> DONG notes that 66kV equipment could be used in place of 33kV.

expected to start within a few months and final investment decisions on more than one OTM-using project expected within 12 months. Versions of the the OTM concept with and without a turbine sharing the substructure are shown in figures 3 and 4 below.



Figure 1: ABB distributed AC collection concept – overview (left) and plan view of equipment (right). Source: ABB published paper.



Figure 2: DONG Distributed Substation concept. Source: DONG Energy published paper.



Figure 3: Siemens OTM: integrated version with both wind turbine and substation topsides sharing a single substructure. (Contrary to appearances in this image the wind turbine tower goes through a hole in the substation deck and connects directly to the substructure). Source: Siemens press release.



Figure 4: Siemens OTM: standalone version with the substation topsides mounted on its own substructure. Source: Draft Decommissioning Programme for Beatrice wind farm, as published on SSE website.

#### 4 THE SIEMENS OFFSHORE TRANSFORMER MODULE

Siemens uses the term Offshore Transformer Module (OTM) to describe its implementation of what this report calls the lightweight substation concept. Using actual project conditions and requirements Siemens has developed two "base design"<sup>16</sup> forms of the OTM: one where the OTM occupies its own substructure ("standalone") and one where the OTM shares a substructure with a wind turbine ("integrated"). These base designs can be modified into a variety of alternative versions in order to meet site-specific requirements and particular requests from wind farm developers.

Distinctive features of Siemens's OTM base designs include the following:

- i) A single transformer with a rating of 320MVA. This is larger than any offshore transformer currently in service<sup>17</sup>, although TenneT does plan to use 400MVA transformers for its Dutch AC offshore substations. This very high transformer rating allows the connection of 290MW of wind generation to a single OTM. In fact, although the OTM is a "lightweight" substation it can connect as much generation as ten out of the sixteen much heavier "traditional" substations listed in table 4!
- ii) The single transformer is insulated and cooled using a synthetic ester compound (for example Midel 7131) rather than mineral oil. Such compounds have low fire risk and are "biodegradable ... non-toxic and not harmful to aquatic life"<sup>18</sup>, which simplifies fire and environmental protection. This is understood to be the first use of a low-flammability alternative to mineral oil for a high voltage offshore transformer.
- iii) The substation topsides are intended to be mounted on a substructure whose design and size closely follows that used by the wind turbines it serves. Furthermore, with the integrated design it is possible for this substructure to accommodate *both* a wind turbine *and* the substation topsides.
- iv) The base case is to have no permanent emergency diesel generator, which reduces cost, weight and fire risk. All UK offshore substations to date have included emergency diesels<sup>19</sup>, as has DONG's lightweight concept, so this appears to be a unique design decision.

<sup>&</sup>lt;sup>16</sup> In other sectors the term "reference design" is used to describe a design which has been extensively optimised with the intention that many, if not all, future projects can be implemented by applying only modest modifications. In this report, however, we use Siemens's terminology where this is referred to as a "base design".

<sup>&</sup>lt;sup>17</sup> Excluding transformers that form part of AC/DC converter stations.

<sup>&</sup>lt;sup>18</sup> Source: website of M&I Materials (manufacturer of Midel 7131).

<sup>&</sup>lt;sup>19</sup> In the UK these generators are intended solely to supply the platform itself. In Germany it is common for platforms to include larger generators that can supply emergency power to the wind turbines in the event of a grid failure.

#### 4.1 Standard Features

The table below summarises the standard feature of Siemens's OTM base designs. A more comprehensive version of this table is found in Confidential Appendix A.

#### Table 5: Siemens OTM base design features

Component	Base Design Features
Transformer	<ul> <li>220/33kV or 220/66kV</li> <li>320MVA (290MW) ONAN rating (no radiator fans, no coolant pumps)</li> <li>Synthetic ester coolant/insulator; no fire suppression system</li> <li>The transformer is outdoors</li> <li>Cooler banks are mounted directly to the tank.</li> <li>Cooler banks have individual isolation/fill/drain valves.</li> <li>The transformer is protected by MV and HV surge arrestors</li> <li>An earthing/auxiliary transformer is integrated within the main transformer tank</li> </ul>
220kV switchgear container	<ul> <li>Three 220kV switchgear bays. (Number can be varied as an option).</li> <li>No circuit breakers (can be added as an option).</li> </ul>
MV switchgear container	<ul> <li>33kV or 66kV switchgear.</li> <li>A cast resin auxiliary transformer (step down from 33kV or 66kV to 400V).</li> </ul>
Control container	<ul> <li>Contains panels for 220kV protection, substation control system, wind turbine SCADA, DTS, communications and tariff metering systems.</li> <li>Also contains auxiliary power distribution (400V AC, 110V AC, 110V DC), batteries, inverters and rectifiers.</li> </ul>
Emergency refuge	<ul> <li>Where a wind turbine and substation share the same substructure, the wind turbine will provide an emergency refuge for substation workers as well as turbine workers.</li> <li>With a standalone substation an extra container is provided which contains offshore survival kits, evacuation/rescue equipment and first aid equipment, along with basic lighting, heating and power outlets. This container is strictly for emergency use with access by an "in emergency break glass" key.</li> </ul>
Access for personnel and equipment	<ul> <li>Boat landings on substructure – as designed by substructure designer.</li> <li>Ampelmann access gate.</li> <li>Where a wind turbine and substation share the same substructure, the heli-hoist area on top of the turbine nacelle may also be used by substation workers.</li> <li>For the standalone substation a heli-hoist area is provided on top of the containers. The area is dimensioned and marked to match the heli-hoist areas on turbine nacelles.</li> <li>Platform crane.</li> </ul>

#### 4.2 Optional Features

Siemens can modify the equipment and substation topsides to meet customer requirements. Modifications that the authors have discussed with Siemens are described below, but it should be noted that this is not intended to be a comprehensive list including all possible modifications:

- i) <u>Changing the transformer rating</u>. Customers may specify transformers that are larger or smaller than the 320MVA (290MW) base case. Siemens have indicated that connecting as much as 350MW to a single OTM should be possible, with a modest increase in topsides weight, and lower transformer ratings are also possible. However a lower rating will not cause the transformer's weight or cost to reduce proportionately, and so the per-MW weight and cost of the platform will increase. Similarly, the transformer's voltage could in principle be reduced below 220kV, but this would imply either a lower rating transformer or multiple export cables connecting to a single transformer; best results are therefore expected at 220kV.
- ii) <u>Fitting a shunt reactor</u>, which is a requirement for projects with long cable connections. Siemens offers a version of the OTM with a shunt reactor. As will be shown in Section 7.6 below, it should generally be possible to accommodate a shunt reactor without requiring additional lifts for topsides equipment.
- iii) <u>Changing the number of 220kV switchgear bays.</u> The base design provides three 220kV switchgear bays: one for the export cable, one for the transformer, and one for a 220kV cable that would connect the OTM to another OTM within the same wind farm. The number of bays can be reduced to two if an OTM-to-OTM connection at 33kV or 66KV is provided instead, as has assumed in Section 8.7 below. Alternatively, an extra bay can be added to connect a shunt reactor.
- iv) <u>220kV circuit breakers.</u> The OTM base design provides no 220kV circuit breakers, which is the norm in the UK where a single export cable is connected to a single transformer. However 220kV circuit breakers can be provided if required for technical reasons (e.g. if the export cables are very long) or if preferred by developers (e.g. having circuit breakers will simplify operations if one export cable serves several OTMs, or if a 220kV ring topology is used). Adding circuit breakers will require a small increase in the size of the 220kV container.
- v) <u>Emergency diesel genset.</u> As will be discussed further below, the OTM relies on backup supplies from other OTMs in the same wind farm, and the ability to fit a temporary diesel genset, rather than having a diesel genset permanently fitted. While our analysis concludes that this approach is reasonable, a permanent diesel genset can be fitted if this is a requirement of the wind farm developer.
- vi) <u>Larger platform crane.</u> As will be discussed further below, the crane specification for the OTM base design has yet to be completed and the crane's capability may be limited. If this is the case then a more capable crane can be provided at customer request.

#### 5 ISSUES AND MITIGATIONS - SAFETY

Siemens – in conjunction with potential clients – has undertaken risk assessments of the OTM concept and have considered the safety design and the reliability/availability/maintainability (RAM) implications of the OTM base design. This section describes the safety issues, and explains how these have been considered, while the next section deals with RAM issues.

## 5.1 Fire Protection

Existing offshore substations show a wide variety of approaches to fire suppression. At the low end some platforms provide minimal fire suppression equipment and rely on passive measures such as fire walls and dump tanks to slow the spread of fire and allow personnel to escape. At the high end some platforms provide active fire protection systems covering almost every room and piece of equipment.

The OTM is towards the upper end of this range:

- i) The main transformer's fire risk is reduced by the use of a "fire safe" synthetic ester. DNV standard DNV-OS-J201 states that the suitable fire protection for a transformer is a "foam system or water mist system"<sup>20</sup>. Siemens have approached DNV who have confirmed that the use of a fire-safe synthetic ester will also meet the requirements of DNV-OS-J201 provided that Siemens can demonstrate that an equivalent level of safety is achieved with their ester solution as would have been achieved with foam or water mist. Insurance underwriters have also stated that this evidence is important for their assessment of the OTM. Given the properties of synthetic ester, Siemens expect that they will be "comfortably able" to demonstrate performance comparable to foam or mist during the detailed design phase of the first OTM projects.
- ii) It should be noted that, regardless of the outcome of the DNV-requested study referred to above, the OTM definitely provides better transformer fire protection than several UK offshore substations. There are several substations already in service with OFTOs which have transformers filled with flammable oil and no active transformer fire protection whatsoever, or which have systems whose effectiveness is highly doubtful.
- iii) All equipment containers use the same fire protection philosophy as has been applied by Siemens for the equivalent rooms on its previous offshore substations.
- iv) The emergency accommodation container (where present) is provided with a portable fire extinguisher, in line with DNV-OS-J201's recommendation for accommodation spaces that are normally unmanned.

## 5.2 Blade Clearance

When the integrated version of the OTM is used with Siemens's own 7MW wind turbine and a

<sup>&</sup>lt;sup>20</sup> See table 6-3 and Section 6, clause 5.1.7

standard-height turbine tower there is a 2.5m clearance between the top of the transformer conservator and the rotating blade tip. The conservator lies above the transformer tank and is not accessed as part of routine O&M activities.

With non-Siemens turbines clearances may vary and it is possible that a turbine that shares the same substructure as an OTM module will need a slightly taller tower in order to provide adequate clearances.

## 5.3 Hazard Identification (HAZID) studies

Siemens made available for review the outputs from two HAZID studies on the base case project. One HAZID examined the standalone OTM base design. The other study was a comparative HAZID that examined what additional hazards might arise with the integrated version of the OTM. The HAZID studies were undertaken by groups that included various representatives of the wind farm developer (including their Operations and Maintenance personnel), DNV, Siemens, and an external safety specialist.

The table below shows those hazards from the HAZID study of a standalone OTM substation that were rated as "high risk".

Risk Description (from HAZID undertaken by developer, Siemens, DNV, etc)	Comparison with other substation designs (by the authors of this report)
Leak/spillage of diesel from temporary diesel generator used during substation commissioning.	<ul> <li>Risk may be reduced relative to a conventional substation where there will be a permanent diesel genset and permanent diesel fuel storage on board the platform. On the OTM this risk only exists during the commissioning phase and in the (very unlikely) event of multiple equipment failures.</li> </ul>
Fall from height, especially from scaffolding during platform installation or if deck panels are removed for cable pulling.	<ul> <li>The single-deck layout of the OTM may give a reduction of risk – there is less scaffolding required due to the single deck level.</li> <li>Siemens has indicated that the method of export cable termination (at deck level rather than from below) should also reduce risks. This has not been reviewed by the authors.</li> </ul>
Dropped object during major lifts (jacket installation, topsides, installation, transformer repair/replacement).	• The simple single-deck structure will have fewer major lifts during construction: a large multi-deck structure will require many more lifts in the fabrication yard.
Air transport / helicopter crash	The same risks apply as on other offshore

Table 6: High Risk items identified by HAZID on standalone OTM

	substations. Note that heli-hoist is not expected to be the normal access method, though this will ultimately be a decision for the OFTO O&M strategy.
Slips/falls caused by water or ice on decks	<ul> <li>Unlike some offshore substations, virtually all outdoor walkways on the OTM have grated surfaces. This is safer than smooth floors which have a higher risk of water ponding or forming ice sheets in cold weather.</li> </ul>
Electrocution, with cable trapped charge being referenced as a particular concern.	<ul> <li>The same risks apply as on other offshore substations.</li> </ul>
Electrical fires in equipment, with batteries being referenced as a particular concern.	<ul> <li>The same risks apply as on other offshore substations.</li> <li>The OTM's control container (which includes the batteries) and the MV container have gaseous fire suppression.</li> </ul>
Manual handling of heavy materials / equipment.	<ul> <li>The same risks apply as on other offshore substations, but the reduced amount of equipment on the OTM (e.g. no diesel genset, no firewater pumps) should reduce the amount of equipment that might need handling for repair or replacement.</li> </ul>

As can be seen from the table above, all of the key risks associated with the standalone OTM are equally or more applicable to larger "conventional" offshore substations.

Siemens also provided the authors with the output of a Comparative HAZID that aimed to identify risks that were specific to the integrated version of the OTM and did not arise in the standalone version. The HAZID identified three areas where material additional risks <u>might</u> exist: objects could be dropped from the wind turbine during installation or maintenance, ice might drop from the wind turbine blades during operation, and any fire on the substation could be a danger to any persons in the wind turbine at the time. For all of these issues, however, mitigating measures were identified, and both Siemens and the developer involved were confident that these mitigating measures would have been successfully applied had a decision been made to proceed with the integrated version of the OTM<sup>21</sup>.

The results of this Comparative HAZID are described further in Confidential Appendix B.

<sup>&</sup>lt;sup>21</sup> The developer in question ultimately decided not to proceed with the integrated version and selected the standalone version. However this was not due to safety concerns but due to concerns regarding the additional contractual interfaces – see Section 7.7.

#### 6 ISSUES AND MITIGATIONS - RELIABILITY, AVAILABILITY & MAINTAINABILITY

This section describes the points that have been raised (by the authors or by other OWPB members) in relation to the reliability / availability / maintainability (RAM) of the OTM concept, and explains how these issues have been dealt with by Siemens.

#### 6.1 Impact of Transformer Faults

Unlike the vast majority of offshore substations (but like the other "lightweight" concepts from ABB and DONG), the OTM carries only a single main transformer. The question therefore arises of what would happen should this single transformer fail.

It is important to note that the size of modern wind farms is such that – even with its capacity of 290MW – a single OTM would not be sufficient to connect any of the UK wind farms currently under construction or with secured  $CfDs^{22}$ . It is therefore more relevant to examine the situation where two OTMs are deployed to connect an offshore wind farm. In this case each of the OTMs can provide a degree of backup to the other. This can be done in one of two ways:

- i) If the OTMs are some distance apart then it may be appropriate to provide a normally open connection between a string of turbines that normally feeds one of the OTMs and an adjacent string of turbines that normally feeds the other. At a minimum this will provide a means of supplying wind turbine auxiliary systems in the event of a transformer fault. With several such connections and higher capacity array cables it may be possible for the wind turbines that usually feed the OTM whose transformer has failed to continue to operate normally at times of low-to-medium wind speed.
- ii) Alternatively, the two OTMs may be directly connected by running medium voltage cables between them. With cables of sufficient capacity this becomes electrically equivalent to a single conventional substation with two transformers. This approach is most likely to be economic when the two OTMs are close together (reducing the cost of the interconnecting cables) or where the array voltage is 66kV (which will give fewer interconnecting cables and much lower per-MW cable costs).

This is dealt with further in section 8 (cost reduction) below.

The SQSS (Security and Quality of Supply Standard) for offshore wind connections contains a requirement for at least two transformers be used on wind farms of more than 90MW. National Grid has recently published a note<sup>23</sup> clarifying that this means that there should be at least two transformers serving a *wind farm*; these transformers do not necessarily need to be on the same *platform*. The dual-OTM approach described above is therefore fully compliant with the SQSS.

<sup>&</sup>lt;sup>22</sup> Burbo Extension is an exception – but even here a single-transformer OTM could have been used with 33kV interconnections to the original Burbo wind farm providing a degree of redundancy.

<sup>&</sup>lt;sup>23</sup> See "Guidance Note - Use of Singe Transformer Offshore Platforms for Offshore Generation Connections Greater than 90MW" by GSR020 Working Group. Also the associated report and open letter.

#### **Experience with Synthetic Esters** 6.2

There is limited experience with the use of synthetic esters such as Midel 7131 as a coolant / insulant for transformers at 220kV and above: M&I Materials, Midel's manufacturer, has provided a reference list which shows only a single transformer in 2004 and two units in 2010.

In 2013-14, however, National Grid undertook a research project where a test article (a "representative sample of a full size winding" from a 400/132kV transformer) was immersed in Midel 7131 and subjected to lightning impulse testing. Based on this National Grid gained sufficient confidence in Midel 7131 that it ordered three Midel-filled 240MVA 400/132kV transformers from Siemens, and these are currently being installed. This seems to confirm that the use of Midel 7131 at 220kV should no longer be considered technologically risky<sup>24</sup> – at least for manufacturers with relevant experience in using the material.

Wind farm developers were asked if they knew of particular reasons for the non-use of esterfilled transformers on previous offshore substation projects. No reasons were identified other than lack of experience with this class of coolant.

#### 6.3 **Offshore Logistics**

The OTM base design provides for personnel access to the offshore substation by crew transfer vessel, a walk to work solution (Ampelmann) and a heli-hoist. In general, the guiding principle is that the offshore substation should be accessible by the same means as the wind turbine towers.

No helideck is provided, which is consistent with the design decisions made by almost all UK offshore substations, but differs from the norm in Germany and Denmark. In the Netherlands TenneT has analysed the need for a helideck<sup>25</sup> and concluded that the extra cost (€3-4m capex, plus additional opex) cannot be justified as there are only limited circumstances in which the presence of a helideck will accelerate repairs, i.e. where heavy equipment is not required for the repair, and where weather conditions are adequate for helicopters but not for crew transfer vessels. TenneT's conclusion is consistent with Siemens's approach to OTM access.

The base design OTMs are to be equipped with cranes that will be able to:

- i) Lift a temporary diesel generator from a crew transfer vessel should multiple cable or transformer faults cause the loss of all auxiliary power on the OTM. (This would involve the crew transfer vessel providing electrical power to the crane or the crane being operated manually).
- ii) Lift replacement radiator units from a crew transfer vessel should replacement be needed (see 6.6 below), and lower the replaced radiator units down to a crew transfer vessel. This allows all radiator units to be replaced using only one of the wind farm's crew transfer vessels.

<sup>&</sup>lt;sup>24</sup> Given the relative newness of synthetic esters at these voltages, however, wind farm developers may nevertheless wish to apply additional monitoring to transformer design, manufacture and testing. <sup>25</sup> See TenneT position paper T.4 "Access to Platform".

On most conventional offshore substations the crane is sized to lift even the heaviest spare parts (other than main transformers and shunt reactors) that might need to be brought on board. Siemens intends to undertake studies at the detailed design stage that will determine the detailed platform crane specification for the base OTM, and hence the range of spare parts that can be lifted on board the platform without an external crane.

Because the base OTM's detailed crane specification has yet to be drawn up, it is not currently possible to determine whether insufficient platform crane capability could lead to a requirement for an external crane to undertake certain repairs, which could in turn lead to these repairs taking longer on the OTM than on a conventional substation. In any event, Siemens have confirmed that they can provide an OTM version with an uprated crane should customers conclude that this is desirable.

## 6.4 Space for Maintenance and Repairs

Siemens have confirmed that clearance around the switchgear and control panels for maintenance, testing and repair is in line with their own manufacturer's recommendations for onshore installations and their previous practice for offshore installations.

Siemens have confirmed that the MV switchgear container and the control container allow repairs to be executed within the container. This can involve either removing and replacing the affected elements (e.g. individual MV switch panels) or their repair *in situ*. In the case of a particularly serious failure the entire container can be removed and replaced.

The 220kV switchgear container does not include a gantry crane. At the detailed design stage Siemens will investigate how to undertake smaller repairs (e.g. replacement of a VT) without the gantry crane. Should the switchgear be seriously damaged the roof of the 220kV switchgear container can be removed by an external crane to facilitate repair or replacement.

Space has been provided to facilitate transformer cooler replacement. This is described further in section 6.6 below.

## 6.5 OFTO / Generator Segregation

Some UK offshore wind farms have made particular efforts to segregate OFTO-owned and generator-owned equipment into separate rooms. The OTM base designs do not make provision for separate rooms, although they do accommodate OFTO and generator equipment in separate lockable panels.

Similarly some UK offshore wind farms provide separate substation control systems<sup>26</sup> for OFTO owned assets (typically the high voltage switchgear, transformers and platform services) and the generator owned assets (typically the medium voltage switchgear on the platform and on each turbine). While more expensive, this arrangement avoids the need for one party to have access to the other's substation control system in order to control their own assets. We understand that in the base OTM design, as in most older UK substations,

<sup>&</sup>lt;sup>26</sup> The substation control systems are frequently called "SCADA systems". This terminology is not used here in order to avoid confusion between the substation control systems (which are usually based on the IEC 61850 standard) and the wind turbine SCADA system.

only a single substation control system is provided.

Since the majority of UK offshore substations are maintained and operated by the host wind farm, under contract to the OFTO, there is a rationale for reducing cost and construction-stage complexity by providing only a single substation control system. However, whether or not the host wind farm will undertake transmission O&M will not be known until after an OFTO has been appointed, and a number of wind farm developers have expressed a strong preference for segregated substation control systems.

Siemens has confirmed that there is sufficient panel space in the OTM's control container to allow two substation control systems to be fitted (nearly all of the extra equipment would be onshore). They can, therefore, offer segregated generator and OFTO substation control systems to customers as an optional extra.

#### 6.6 Corrosion

The offshore environment is highly challenging from the point of view of corrosion. A particular issue is likely to be the transformer coolers which are difficult to repaint in the field and where the metal must be thin to allow efficient heat transfer.

Siemens have mitigated the impact of transformer cooler corrosion by allowing coolers to be replaced easily should this become necessary. This is not always the case on offshore substations, with many requiring an external crane to remove the transformer room roof, and/or lacking valves to shutdown individual coolers, so that the whole cooler bank must be replaced as a single unit by an external crane while the transformer is out of service.

Siemens has shown the authors a "storyboard" describing how individual cooler banks can be isolated, drained of oil, lowered to the deck, moved to the platform crane and then lowered to a crew transfer vessel, while replacement coolers are installed by reversing this process. Cooler replacement can be undertaken one unit at a time without needing to shut down the transformer, and the process should not require any ships other than a standard crew transfer vessels to deliver or lift replacement parts or tools.

#### 6.7 Auxiliary Power

Auxiliary power for the OTM can be taken from one of three possible sources:

- i) In normal operation auxiliary power is taken from the earthing/auxiliary transformer within the main transformer tank.
- ii) Should the main transformer fail, or need to be taken out of service for routine maintenance, then the normally open MV connections between the affected OTM and other OTMs within the same wind farm (see section 6.1) can be closed, re-energising the substation MV busbar. Substation auxiliary power is then maintained through the auxiliary transformer in the MV container.
- iii) In the event of a complete grid failure that affects all of the wind farm's offshore substations (e.g. an anchor drag that damages all export cables) a temporary diesel generator can be lifted

onto the OTM's deck and plugged into the 400V switchboard. As noted in section 6.3 above, the intention is that this operation can be undertaken using only a crew transfer vessel and the platform's own crane. This temporary generator would also be used during commissioning.

The absence of a permanently installed standby diesel generator on board the OTM is a significant difference from all existing UK offshore substations, and all non-UK offshore substations known to the authors. By making use of interconnectors to other OTMs in the same wind farm, however, the circumstances under which a permanently installed diesel might be required become very limited. Indeed it is likely, given the known reliability problems of diesel generators, that the auxiliary power on board an OTM that is interconnected to a neighbouring OTM would be more reliable than would be the case on board a conventional substation with a single export cable and a backup diesel generator.

Based on the high level of auxiliary-power reliability expected thanks to being able to draw power from neighbouring OTMs, combined with the ability to lift an emergency generator onto the OTM in the event of an extreme failure, the authors conclude that not having a diesel generator on board the OTM is acceptable. They also note that removing the generator (and diesel fuel) from the platform is expected to give significant reductions in O&M cost and complexity.

#### 6.8 Cable Pull-in

Siemens have undertaken a considerable amount of work planning the pull-in of cables to the OTM in order to confirm that the process will not be affected by the size of the OTM's cable deck area, which is smaller than in most conventional offshore substations.

The authors were given access to detailed storyboards illustrating the proposed pull-in process. These showed the pull-in winch mounted on the main topsides deck, with the pull-in wire running to the top of a J-tube over pulleys (some mounted on temporary A-frames) and through slots in the topsides deck which would be covered by gratings in normal operation.

In addition, to simplify the pull-in and termination of the 220kV export cable the 220kV switchgear's cable terminations are not vertical (the usual arrangement) but angled at 45°.

#### 7 OTM STRUCTURAL DESIGN

The OTM concept can be used with a number of types of substructure: the principle is that rather than having a custom-designed substructure the OTM should sit on a substructure adapted from whatever has been designed for the turbines in the wind farm served by the OTM. In this way the OTM can take advantage of the economies of scale created by the "mass production" of substructures for the wind turbines (typically there might be 40 or more turbines for every OTM<sup>27</sup>).

The large number of wind turbine substructures produced means that decisions regarding substructure type, weight and stiffness will be driven by the need to minimise the cost of wind turbine substructures. The substructure designer<sup>28</sup> will then have to take a substructure that has been optimised for wind turbine service and adapt it the serve a standalone OTM or an integrated combination of turbine and OTM. Fortunately, Siemens's experience to date – and their expectation for the future – is that this adaptation of the substructure design won't involve significant weight increases or significant changes to the fabrication and installation works.

#### 7.1 Standalone OTM on Jacket Substation Substructure

It is current practice for substation substructures to be built with higher safety factors (the "design fatigue factor", see 7.3 below) than wind turbine substructures. However, the dynamic loading imposed by the OTM is so much lower than that imposed by a 7-8MW wind turbine that – even if the higher safety factor typically applied to substations is used – it is still possible to accommodate the OTM on the essentially same design of jacket as the turbines in the same wind farm.

The OTM base designs were developed on a project where a four legged jacket substructure had already been selected as the optimum for the wind turbines. These jackets, which stand in depths of around 45m, weigh about 800-900t in both wind turbine and OTM variants. While some work on the OTM jacket design is still ongoing (for instance different options are being explored for the J-tubes<sup>29</sup> and for the connection between the jacket and the OTM) Siemens has been able to confirm that these issues will not lead to significant changes in the size, framing and installation of the OTM jacket relative to the wind turbine jackets; this ensures that the expected economies of scale can be achieved.

#### 7.2 Integrated OTM on Jacket Substructure (shared with Wind Turbine)

The integrated design makes use of a layout where all equipment is moved away from the centre of the topsides deck, leaving space for a circular hole that the turbine tower is lowered down through. Note that there is no connection between the OTM topsides deck and the wind

<sup>&</sup>lt;sup>27</sup> 290MW-per-OTM divided by 7MW-per-turbine

<sup>&</sup>lt;sup>28</sup> It is likely to be most cost effective if the company that has designed the wind turbine substructures also works out the modifications to the substructure design needed for OTM service.

<sup>&</sup>lt;sup>29</sup> Since a substation has many more cable connections than a wind turbine the substructure for the substation must support a significantly larger number of J-tubes. The J-tubes must be carefully arranged so that their supports do not overstress the jacket bracing, and even with this careful arrangement certain key areas of the jacket may need to be strengthened.

turbine; instead the turbine is supported directly on the jacket transition piece, as is the case for the "regular" turbines in the wind farm (i.e. those that don't share a substructure with a substation).

The jackets used by the integrated OTM base design, the standalone OTM base design and the turbines in the wind farm for which the base design was developed are all very similar in design and weight. The factor of safety ("design fatigue factor") used in validating the substructure design, however, varies between the three roles. This is discussed further in section 7.3 below.

The extent of movement and acceleration that would be experienced by high voltage equipment on the integrated OTM was analysed by the base case project's substructure designer. These calculations indicated that the peak accelerations on the base integrated OTM would be less than on a conventional monopile-supported substation. Indeed Siemens has supplied equipment to one monopile-supported offshore substation where the peak accelerations are nearly 3 times greater than the value predicted for a jacket-supported OTM with integrated wind turbine. The acceleration values calculated by the substructure designer are provided in Confidential Appendix C.

## 7.3 Design Fatigue Factor

Fatigue design of steel structures is usually based on the use of S-N curves (i.e. curves plotting S, the level of cyclical stress applied to a material, against N, the number of cycles to a given probability of failure). These curves are used to calculate a fatigue life based on the loading spectrum that the structure will see. A design fatigue factor (DFF) is then applied to the calculated fatigue life, with this factor dependant on the required safety level of the structure, and the ability to inspect the joint for which the fatigue life is being calculated.

DNV-OS-J101 is the structural design code most commonly adopted for the design of offshore wind turbine substructures. This code specifies that a DFF of 3 should be adopted for the fatigue design of wind turbine substructures in locations where no inspection is planned. This gives an annual probability of failure of  $10^{-4}$ , which is considered appropriate for a normally unmanned structure.

DNV-OS-J201 is the DNV design code usually used for offshore substations and their substructures. This code specifies that a DFF of 10 should be used in the design of these structures in locations where no inspection is planned. This corresponds to an annual probability of failure of  $10^{-5}$ , an order of magnitude lower than for the wind turbine<sup>30</sup>.

As noted in the previous section, the jackets used by the integrated OTM base design, the standalone OTM base design and the turbines in the wind farm are all very similar in design but have different DFFs applied:

<sup>&</sup>lt;sup>30</sup> The rationale behind using a DFF of 10 for an offshore substation is not explained in DNV-OS-J201. It is interesting to note that in other design codes (most notably API RP 2A, which is predominantly used by the Oil and Gas sector), the use of a DFF of 10 is recommended for "failure critical" structures – a category based on the probability of personnel injury/fatalities – and the DFF can generally be reduced to 5 for unmanned structures.

- i) For jackets used by wind turbines a DFF of 3 is used, in line with DNV-OS-J101.
- ii) For jackets used by standalone OTMs a DFF of 10 is used, in line with DNV-OS-J201.
- iii) For jackets shared by wind turbines and integrated OTMs using a DFF of 10 would result in a circa 45% increase in the integrated OTM's jacket weight, which could make it impossible to install using the same vessel as the wind turbine jackets. As a result of this a reduced DFF of 6 was selected for the integrated OTM's jacket: this allows the integrated OTM's jacket to be built with only minor changes from the standard turbine jacket and at weight that is only 10-15% higher<sup>31</sup>.

Siemens has discussed using a DFF of 6 with DNV, who have provided a letter in relation to one of the projects that Siemens are working on confirming that they would certify a design based on this DFF provided that:

- i) The wind farm contains more than one OTM with some degree of redundancy. (As noted in section 6.1, this is expected to always be the case for future British wind farms although some wind turbine strings could be disconnected if an OTM were to be completely lost).
- ii) The lower DFF is acceptable to the client. (We understand that the lower DFF was not a concern for the project developer; certainly it was not raised as a concern in the HAZID studies).
- iii) The OTM is normally unmanned. (The OTM concept includes no provision for persons staying on board for longer than a single work shift; the emergency refuge is strictly for emergency use only).

#### 7.4 Integrated OTM on Monopile Substructure (shared with Wind Turbine)

A preliminary engineering study has been carried out by an experienced turbine monopile designer to check the effect of adding substation topsides to a wind turbine supported by a monopile substructure. Substation topside weights ranging from 250t to 1300t were considered, and represented by a mass added to the finite element model of a monopile in water approximately 30m deep, with a 6MW Siemens wind turbine and sandy soil being assumed.

The results suggested that for a 1090t substation topside there would be an increase of 13% (1487t to 1687t) in the monopile weight and an increase in monopile diameter from 8m to 8.2m. There would be only a very small change in the first natural frequency of the structure, and while there would be a more significant change in the second natural frequency, it would not be sufficient to take the natural frequency outside the range required by the wind turbine manufacturer. It should be noted that, as the focus of this study was on changes to natural frequency, no increase to DFF was taken into account above the DFF of 3 normally specified for a wind turbine. Nor was consideration given to the impact of the multiple J-tubes that

<sup>&</sup>lt;sup>31</sup> Weight calculations were undertaken by the substructure designer retained by the base project's developer.

would be required by a substation.

This initial work is encouraging in suggesting that an integrated OTM could work with a monopile substructure. Nevertheless, any developer wishing to pursue this option will need to undertake a full feasibility study using site-specific data (preferred turbine parameters, water depth, metocean, geotechnical, etc). For new projects this study can be incorporated into the structural design studies that will be required in any event to identify the optimum wind turbine substructures.

A particular concern has been raised over the movements and accelerations that equipment placed on a monopile structure with a wind turbine. This will need careful consideration and collaboration between electrical equipment manufacturers and structural designers to ensure the forces equipment is subject to over its lifetime are tolerable. The Offshore Wind Programme Board has funded a basic study by ORE Catapult that analyses accelerations recorded at the wind turbine tower-base level where any substation topsides would be situated.

#### 7.5 Substation Topsides Structure

The topsides structure for the OTM base design weighs a total of 660 tonnes. With the 320MVA transformer able to accept up to 290MW of wind power this gives the design a "power density" of 440kW/tonne – substantially better than any other offshore substation for which weight information has been found, and 75% better than the best project in table 4 with "conventional" enclosed transformer rooms.

It should be noted that this low weight is not driven by a reduction in the weight of the "payload" (the mechanical and electrical equipment on board the platform): most (c. 85%) of the payload weight on any offshore substation is the transformers (and shunt reactors, if any), and the OTM's transformers are not particularly light on a per-MVA basis<sup>32</sup>. Similarly, the simplification of auxiliary equipment will not change the payload weight significantly since this equipment is not a major part of the total payload weight: a 100kVA diesel generator, for instance, only weighs slightly more than one tonne.

Instead the source of the OTM's excellent power density is the low structural weight of the topsides relative to the payload. On the OTM the weight of the topside structure is about 75% of the weight of the payload (if the weight of the containers is included within the structure), or 50% of the weight of the payload if the weight of the containers is included in the payload<sup>33</sup>. On a typical conventional substation, in contrast, the structural weight would be around 150% to 200% of the payload.

In the opinion of the authors this reduction in structural weight relative to the payload weight may be attributed to a number of factors, including:

<sup>&</sup>lt;sup>32</sup> As was noted previously, larger transformers tend to have a lower weight per MVA. This phenomenon is not visible with the OTM transformer when its weight is compared to transformers on conventional substations. This may be due to its use of ester coolant, or because it has no cooling fans or pumps.

<sup>&</sup>lt;sup>33</sup> Hence for outdoor equipment, like the transformers, the topsides structural weight adds 50% to the weight of the equipment.

- i) There is a very large reduction in enclosed volume compared to a conventional "multideck" offshore substation with enclosed or part-enclosed transformers. For instance, one recent substation with two large transformers was examined and found to have a total enclosed volume of nearly 2000m<sup>3</sup> per transformer. More than half of this of this relates to the transformer rooms: on the OTM this volume is eliminated entirely. The remaining volume is reduced by a quarter on the OTM by eliminating the diesel generator room, store rooms, work stations, a kitchen/mess-room, a toilet/wash-room and a locker room.
- ii) The single-deck OTM design is less rigid than a multideck platform. Rather than adding weight to reduce this flexibility Siemens have designed the OTM deck to accommodate a degree of flexibility while still ensuring that deflection requirements are met during all loading conditions. Where deflections are predicted these have been accommodated through, for instance, making the transformer high voltage connection using flexible 220kV cables rather than rigid 220kV gas insulated busbars, and using bearing contacts and stiff subframes to support equipment that needs to be rigidly mounted.
- iii) Siemens has been able to spend longer on optimising the design than is usual for wind farm substations: there is anecdotal evidence that structural design frequently needs to be undertaken in accelerated timescales, leading to simpler – but heavier – solutions being adopted.

#### 7.6 Verifying the Feasibility of an OTM with Shunt Reactors

As noted in section 4.2, one of the OTM versions available from Siemens incorporates a shunt reactor. Discussions within the Offshore Wind Programme Board have indicated that this is an important feature for many wind farm developers.

In order to verify that a shunt reactor can be accommodated without the weight of the OTM topsides reaching the point at which more than one lift will be required, the authors undertook a brief proof-of-concept analysis. It was assumed that a 90Mvar shunt reactor would be required, as this is the size included in the DONG distributed substation concept. The authors do not have accurate information on the weight of a 90Mvar ester-filled shunt reactor, but by scaling from onshore shunt reactors it was concluded that a range of 100-120t was likely.

Adding 50% to this weight to account for the additional topsides structure required to support the reactor gives a total additional weight of 150-180t. Adding this to the 660t total weight of the base OTM design gives a total estimated weight for an OTM with a shunt reactor of 810-840t.

The estimated weight is below (if rather close to) the estimated maximum weight that could be accommodated by all nominally "1000 tonne" cranes (see Section 3). It should, therefore, be possible to install an OTM with a shunt reactor without needing any additional heavy-lift operations<sup>34</sup>.

<sup>&</sup>lt;sup>34</sup> Though given the scale of the cost savings shown in Section 8, there would only be a limited impact on the economic benefits

## 7.7 Contractual Interface Considerations

On previous UK projects the design and build of the offshore substation has been undertaken using a wide range of contractual approaches, with multi-contract arrangements (where the substation topside, substation substructure, heavy-lift and sometimes major electrical items are covered by separate contracts) being most popular.

There is some anecdotal evidence that the alternative "turnkey" approach (where substation topsides, substructures and installation are integrated into a single contract) is becoming more popular for new offshore substations, presumably because of the simplification and reduction of contractual interfaces. As noted in Section 3.3 above, lightweight substations (including the OTM) tend to cut across the turnkey approach:

- i) It is likely to be more cost effective to have the OTM substructures designed, built and (where applicable) installed by the wind turbine substructure contractor who is already undertaking this work on maybe 70-80 other substructures. Such savings can be expected to more than offset any impact from introducing an additional contractual interface.
- ii) The OTM concept involves using the same heavy-lift vessels to install the substation and the wind turbines. The reduction in programme risk that this provides (since the heavy lift vessel used for substation installation will be available on site for a prolonged period rather than for a narrow window) is expected to far outweigh any impact from introducing an additional contractual interface.

Where the substation topsides and a wind turbine are being accommodated on the same substructure some additional complexities arise:

- i) Siemens's OTM base design is based on using a Siemens 7MW wind turbine. However, Siemens have stated that the hole in the middle of the topsides deck could be reduced or increased in size to accommodate any of the 7–8MW wind turbines that are currently on the market – including equipment manufactured by their competitors. It should be noted that there is no physical connection between the wind turbine and the substation topsides: the wind turbine connects directly to the substructure.
- ii) The substructure design contractor, who might be working directly for the developer or as a subcontractor to the turbine substructure supplier, will need to receive design data from both the substation supplier and the turbine supplier. It is noted that there are often sensitivities around such data, particularly if the substation and turbine suppliers are competitors. However, it should be possible to put in place suitable non-disclosure agreements to ensure that confidential data from one supplier is not passed to the other.
- iii) There may be liability issues if one contractor physically damages assets provided by another: an extreme example of this would be if a part of turbine were to be

of the OTM concept if it was necessary to lift the shunt reactor separately and terminate the cables to it offshore.

dropped on the OTM. In practice, however, such issues are likely to be covered by the wind farm developer's contractor's all risks (CAR) insurance.

iv) There may be liability issues from delays, design issues, or reduction in asset life that is caused by the provision of incorrect design data from the turbine, substation or substructure supplier. An example would be where the wind turbine supplier provides incorrect data about its turbine, as a result of which the OTM experiences higher long-term movement and accelerations than expected, with an adverse effect on electrical equipment reliability.

The authors understand that at least one potential customer for the integrated OTM has instead opted for the standalone OTM due to the issues set out above, and in particular due to concerns regarding the allocation of liability should long term movements and accelerations prove larger and more damaging than forecast.

Because of the importance of these contractual liability issues for wind farm developers, the Offshore Wind Project Board is considering how best to mitigate these concerns. An initial piece of work to help do this is the independent assessment undertaken by ORE Catapult of the likely magnitude and effect of the movements and accelerations that may be experienced by high voltage equipment in the integrated OTM design. This should help guide the design of a more extensive study that would give developers greater confidence when assessing whether these interface issues are actually problematic or whether they are a minor addition to the integrated risks that are dealt with as a matter of course on current wind farm projects.

## 8 COST REDUCTION

Siemens and a wind farm developer have presented to an industry working group (known as "GSR020")<sup>35</sup> the following values as an example of the savings that can be obtained by using the OTM on a 500MW wind farm project<sup>36</sup>. The savings are as follows:

- i) A cost reduction of £25m (at 2015 prices) from the use of two standalone OTMs in place of a single "conventional" substation. The conventional substation is assumed to be a multi-deck design with flammable-oil-filled transformers, with the transformers (or at least their tanks) being enclosed within transformer rooms. There are no shunt reactors. The £25m total saving is the sum of savings in topsides equipment/fabrication, savings in substructure fabrication and savings in transport/installation costs.
- An offsetting cost increase of £1.5m due to the cost of providing cables between the two OTMs to ensure a degree of redundancy. It is suggested in the GSR020 data that the same cost should apply whether the cables in question are high voltage (220kV) or medium voltage (33kV or 66kV).

The GSR020 group included National Grid and three other wind farm developers, and Siemens notes that these cost reduction figures were accepted by the working group.

## 8.1 Impact of Wind Farm Size

If the notional wind farm being served were to become smaller than the 500MW chosen here then the costs of conventional and OTM substations would fall slightly, but not pro-rata to the reduction in wind farm MW. The savings provided by the OTM will similarly not fall pro-rata to the reduction in wind farm size and so the per-MW saving provided by the OTM would be higher.

If the notional wind farm being served was to become larger than the 500MW chosen here then, by the reverse of the effect discussed above, the per-MW saving provided by the OTM would reduce somewhat. It should be noted, however, that our analysis does not include the impact of longer array cables and higher array cable losses – these are likely to become a substantial factor if a wind farm of as much as 700MW<sup>37</sup> is to be connected to a single central substation.

All existing projects of 500MW or more have two conventional substations, each with at least two transformers. Relative to a design with *two* conventional substations the cost saving from using the OTM concept would be substantially greater.

<sup>&</sup>lt;sup>35</sup> See Annex 3 of the report of working group GSR020. GSR020 is a working group of the SQSS Review Panel. Although the GSR020 figures relate to a specific project, the fact that they were accepted by developers working on other projects suggests that they do not result from unusual site-specific factors. Further work will be undertaken in 2016 by the Offshore Wind Accelerator to quantify the benefits of OTM-type concepts across a range of use cases.

<sup>&</sup>lt;sup>36</sup> It should be noted that the exact savings will vary from project to project due to site specific factors.

<sup>&</sup>lt;sup>37</sup> For wind farms larger than 700MW the relevant comparison would be three OTMs versus one (or, more likely, two) conventional substations.

Because of the factors listed above, it is thought that the cost reduction calculated for a 500MW wind farm is likely to be a conservative estimate, with other sizes of wind farm likely to give similar or higher savings.

## 8.2 Independent Calculation of Cost Savings for a Standalone OTM

This section seeks to validate the cost reductions indicated above by independently calculating the likely savings from public domain sources. This is dealt with in three areas: transport and installation costs, the cost of fabricating substructures, and the cost of fabricating the topsides.

#### Transport and installation costs

Public domain costs for an offshore substation are provided in the document "A Guide to an Offshore Wind Farm", published by The Crown Estate and written by BVG with industry contributions. This provides cost figures for a wind farm with "a single substation [that] can support the input from around 500MW of wind turbines".

This cost of "transfer of the substation [topside] from its quayside fabrication site and installation on the foundation" is given as  $\pm 10m^{38}$ .

The cost of installing the substation jacket and piling it to the seabed is not specified, though since the cost of mobilising a heavy lift vessel would already be included in the £10m topsides installation cost, the cost of jacket installation would presumably be substantially less. For the purpose of this analysis jacket installation is assumed to cost half as much as topsides installation, i.e. £5m. This gives a total installation cost of £15m for the conventional OSP.

Since the OTM would typically be installed by a vessel designed to install 7-8MW wind turbines, a reasonable starting point for the OTM installation cost would be the installation cost of an "8MW class" turbine and its substructure, which has been estimated as £2.8m<sup>39</sup>.

The difference between the transport and installation cost for a pair of OTMs (2 x  $\pm$ 2.8m) and that for a single conventional substation ( $\pm$ 15m) is therefore  $\pm$ 9.4m.

#### Fabrication of substructures

A Guide to an Offshore Wind Farm gives the cost of fabricating the jacket and piles for a 500MW conventional substation as  $\pm 10m^{40}$ .

The cost of a fabricating a jacket substructure for a 7-8MW wind turbine is estimated to be  $\pm 3m^{41}$ . The OTM is intended to use the same substructure design as the surrounding 7-8MW

<sup>&</sup>lt;sup>38</sup> Source: Section I5 of "A Guide to an Offshore Wind Farm".

<sup>&</sup>lt;sup>39</sup> Source: Scaled from graph shown as Exhibit 3.8 in "Offshore Wind Cost Reduction Pathways", a report by The Crown Estate with industry contributions, 2012. Installing the OTM topsides would require only a single lift, rather than the multiple lifts required for a turbine, suggesting a lower cost, while the need to provide special seafastenings and/or to provide a special transport barge for the OTM deck would increase costs. This balance of factors suggests that assuming a similar installation cost for turbines and OTMs is likely to be broadly correct.

<sup>&</sup>lt;sup>40</sup> Source: Section B3.3 of "A Guide to an Offshore Wind Farm". Curiously helipads are also included within this cost category, but these are very rare on UK substations.

<sup>&</sup>lt;sup>41</sup> Source: Section B2 of "A Guide to an Offshore Wind Farm", which states that fabrication of a jacket (plus pin piles) for a

turbines (with minor changes such as additional J-tubes), so its jacket fabrication cost should similarly be around £3m for each OTM.

The difference between the substructure fabrication cost for a pair of OTMs (2 x  $\pm$ 3m) and a single conventional substation ( $\pm$ 10m) is therefore  $\pm$ 4m.

#### Electrical equipment

There is no significant difference in the electrical equipment on the conventional offshore substation and on the OTM: on the conventional substation there will be a pair of transformers, each with its own 220kV and MV gear, while with the OTM option each transformer/switchgear block is placed on a separate OTM. There are some minor additions with the two-OTM option, for instance additional auxiliary transformers, but the cost and weight impacts of these is unlikely to be material.

Costs associated with OTM-to-OTM cables are dealt with separately below.

#### Fabrication of topsides

Each OTM topsides weighs 660 tonnes. This comprises a "payload" part and a "structure" part, with the structure part being 75% of the weight of the payload (see Section 7.5). It follows that the topsides structural weight for a pair of OTMs is  $(660 \times 2) \times (75\% / (100\% + 75\%))$ , i.e. 565t.

As noted in Section 7.5, for a well-designed conventional offshore substation the structural weight is twice as large as for the OTM: 150% of the payload (which is the same) rather than 75%. Thus an additional 565t of topsides structure must be fabricated for a conventional substation that contains essentially the same high voltage equipment as a pair of OTMs.

The cost of topsides fabrication (i.e. the cost of the topsides excluding the cost of the high and medium voltage assets and their control & protection systems) is typically in the range of  $\pm 10$ k/tonne to  $\pm 20$ k/tonne<sup>42</sup>. Thus fabricating an additional 565t of topsides would cost  $\pm 5.6$ -11.3m. This includes both the cost of fabricating the extra structure and the cost of the extra auxiliary equipment (e.g. lighting, heating, ventilation) that scales with the size of the structure being served.

In addition, the OTM design completely eliminates a number of expensive auxiliary systems, notably the transformer fire protection and the diesel generator:

i) National Grid has estimated that the net cost saving from using Midel 7131 (i.e. the reduction in fire protection costs less the increased cost of the transformer itself due to the use of Midel) is  $\pm 235k^{43}$  per transformer, based on a similar size of

<sup>5</sup>MW turbine may cost as much as £3m "depending on water depth". Unpublished data from a study by ORE Catapult suggests that this £3m figure is also reasonable for a 7-8MW turbine at modest water depths. At greater water depths the substructure fabrication cost will be somewhat higher.

<sup>&</sup>lt;sup>42</sup> Publicly disclosed examples include the contracts for Anholt (£14k/t) and Horns Rev 3 (£19k/t).

<sup>&</sup>lt;sup>43</sup> See Network Innovation Allowance Project Registration document for "400kV Synthetic Ester Filled Transformer Pilot Project". The National Grid cost reduction estimate is based on onshore installation.

transformer to that used on the OTM<sup>44</sup>.

A diesel generator, and its associated fuel, cooling and fire suppression systems, ii) typically costs on the order of £200k.

These factors increase the estimated cost saving by £670k (2x£235k + £200k) to £6.3-12.0m.

#### OTM-to-OTM cables

In a conventional offshore substation the MV switchboards are arranged so that if a transformer, or its associated export cable, were to fail then the turbines that it normally serves can be connected to another transformer. As this other transformer will now have to support both the turbines it normally serves, and the turbines whose normal transformer has failed, its capacity won't be sufficient to allow full power output from all turbines. Nevertheless, since wind farms spend most of the time at reduced levels of output this arrangement will allow considerably higher energy exports while the failed transformer or cable is being repaired.

Since the OTM concept has only a single transformer on each substation, providing this level of redundancy requires the addition of cables between the MV switchboards in each OTM.

Where standalone OTMs are used, and where the array cables from the whole wind farm converge at a single point (as is implied here, since the cost impact of array cable changes between the twin-OTM option and the single conventional substation are not discussed), it should be possible to place the two OTMs beside each other: indeed they could probably be bridge-connected<sup>45</sup>. In this case the cost of connecting the two OTMs should be minimal.

## 8.3 Independent Calculation of Additional Cost Savings for an Integrated OTM

If an integrated design is adopted where wind turbines share the offshore substation's substructures then these turbines don't need to provide their own substructures or array cables, with considerable savings. However the two OTMs can no longer be located beside each other since the turbines will need to respect the array spacing; hence the cost of OTMto-OTM cables will increase.

#### Wind turbine substructures

The substructures for a 7-8MW class turbine are assumed to cost £4.8m each, comprising:

- i) A £3m substructure fabrication cost (see section 8.2 above)
- £1.8m for substructure installation. This figure comes from the Cost Reduction ii) Pathways report which indicates a cost of £1.5m<sup>46</sup> for substructure installation on a 4MW turbine, with installation costs for an 8MW turbine being 20% higher<sup>47</sup>.

<sup>&</sup>lt;sup>44</sup> Higher voltage (400kV versus 220kV) but lower power (240MVA versus 325MVA).

<sup>&</sup>lt;sup>45</sup> Bridge connection is already used by the Robin Rigg substations and by some of the HVDC converter stations in Germany.

<sup>&</sup>lt;sup>46</sup> Source: Exhibit 3.18 of "Offshore Wind Cost Reduction Pathways". Substructure installation costs are 61% of a 4MW turbine's overall installation cost of £611k/MW, or £611k/MW x 4MW x 61% = £1.5m. <sup>47</sup> Source: scaled from graph shown as Exhibit 3.8 in "Offshore Wind Cost Reduction Pathways": this shows the overall

Avoiding the need for two wind turbine substructures costing £4.8m each equates to a cost reduction of £9.6m. This calculation does not include factors that might cause the cost of a substructure carrying both OTM and turbine to be higher than the cost of a regular wind turbine substructure. The reasons for neglecting these factors are as follows:

- i) Variations in water depth and soil conditions mean that a wind farm's substructures will all vary in design, and the variation between integrated-OTM and turbine-only substructures is comparable.
- ii) Although the integrated-OTM substructure would be 15% heavier than the turbineonly version, this does not necessarily imply a 15% higher cost. Siemens noted that, in their experience, small changes in weight have limited impact on fabrication cost providing the fabrication approach, facilities and basic design remain unchanged.

#### Wind turbine connection

Having wind turbines standing on the same substructures as the OTMs also avoids the need for two submarine array cables: these turbines can instead be connected directly to the MV switchboard in the OTM.

A Guide to an Offshore Wind Farm indicates that the installed cost of a single array cable is approximately £1m, based on a 500MW wind farm with 100 array cables<sup>48</sup> where the array cables have a supply cost of £20m<sup>49</sup> and an installation cost of £80m<sup>50</sup>. The saving from eliminating two array cables has therefore been estimated as  $2 \times f1m = f2m$ .

Future projects with 7-8MW turbines are expected to have slightly longer and more expensive array cables, but the impact is likely to be small and has been neglected.

#### OTM-to-OTM cables

With the integrated OTM design the distance between two OTMs will need to be at least the turbine array spacing.

For the 500MW wind farm being analysed, the cables between the MV switchboards on each OTM would need to have a total capacity of 125MW if they are to provide a level of redundancy equivalent to a single conventional offshore substation.

The cost of these OTM-to-OTM cables will depend on the array voltage:

i) The largest 33kV array cables in general use carry around 40MW, and at least three such cables would be required to interconnect the two OTMs. A Guide to an

<sup>(</sup>substructure, tower, nacelle and blades) installation cost of a pair of 4MW turbines as £4.6m (hence £2.3m per turbine)

and a single 8MW turbine as £2.8m. <sup>48</sup> The figures in "A Guide to an Offshore Wind Farm" are based around a notional wind farm containing 100 x 5MW turbines.

<sup>&</sup>lt;sup>49</sup> Source: Section B1.2 of "A Guide to an Offshore Wind Farm".

<sup>&</sup>lt;sup>50</sup> Source: Section I3 of "A Guide to an Offshore Wind Farm".

*Offshore Wind Farm* indicates a cost of £1m per cable. Thus, assuming that the two OTMs are at adjacent positions in the turbine array, the cost of interconnection between the OTMs would be  $3 \times 1m=23m$ .

ii) With 66kV array cables the number of cables between the two OTMs would be reduced to two with the cost-per-cable being essentially unchanged<sup>51</sup>. The cost of interconnection therefore falls to  $2 \times \pm 1m = \pm 2m$ .

#### 8.4 MV Cables Optimisation

The benefits calculated above assume that a wind farm contains two OTMs, and that these are close to each other: either bridge connected or (if turbines share their substructures) at adjacent locations within the turbine array. As a result the cable strings connecting the wind turbines are largely unchanged between the design featuring a pair of OTMs and the design featuring a single conventional substation.

Depending on the shape of the wind farm, however, it may be beneficial to separate the two OTMs. Each OTM would then sit at the centre of its own set of wind turbine strings, with interconnections between these strings serving in place of dedicated cables between the OTMs. A study published by DONG<sup>52</sup> suggests that such a "distributed substation" arrangement could have substantial benefits, primarily through reducing the distance that power would have to travel at the array voltage, and hence reducing energy losses in the array cables.

This potential benefit has not been considered in this report, but it is recommended that further work be undertaken to investigate the potential for additional cost reductions through optimising the MV array cables to take advantage of the OTM concept.

#### 8.5 Conclusions in Relation to Cost Reduction

Table 7 below shows the cost reduction provided by the OTM. Two sets of results are presented: one column shows the values presented to the GSR020 group (supplemented by the author's calculation for the integrated option) and the other column is entirely based on the authors' own calculations using public domain sources.

<sup>&</sup>lt;sup>51</sup> The cost of manufacturing wet-type 66kV cables is 10-20% higher for cables with the same conductor area and double the rating (source: DNV report to TenneT "66kV systems for Offshore Wind Farms"), while installation costs are unchanged. Since manufacturing costs are just a quarter of total, it follows that the total cost increases by less than 5% for a doubling of rating and by even less for the 50% higher rating shown here.

<sup>&</sup>lt;sup>52</sup> "Distributed Substations, a cost-efficient multi-platform topology", EWEA Offshore, 2015

Table 7: OTM	A cost reduction	for a	500MW	wind	farm
	1 00001 00001011	101.0	5001111		101111

Area	Savings from GSR020; author's own calculations for integrated option	Savings solely from author's own calculations
Transport and heavy lift of topsides & substructure		£9.4m
Fabrication of substation(s) substructure	£25m	£4.0m
Electrical equipment on board substations		£0.0m
Fabrication of topsides (incl. auxiliary equipment)		£6.3-12.0m
OTM-to-OTM connection for standalone	(£1.5m)	(£0.0m)
TOTAL (Standalone)	£23.5m	£19.7-25.4m
Avoid 2 wind turbine substructures	£9.6m	£9.6m
Avoid 2 wind turbine submarine cable connections	£2.0m	£2.0m
Additional OTM-to-OTM cost for integrated	(£1.0m) <sup>53</sup>	£2.0-3.0m
TOTAL (Integrated)	£34.1m	£28.3-35m
Note: the cells shaded blue contain data derived solely from GSR020. All other cells contain data wholly or partially derived from the author's own calculations.		

As can be seen, the values presented to the GSR020 group are are within the range of values calculated by the authors from public domain sources. This tends to validate the GSR020 values, as does the fact that the GSR020 values were accepted by the three independent offshore wind developers on the working group.

#### 8.6 Cost Saving in £/MWhr Terms

Table 7 indicates that the integrated OTM can reduce costs by  $\pm 34.1$ m relative to a conventional offshore substation. This cost saving is converted into  $\pm$ /MWhr terms as follows:

i) Convert from the £34.1m contract-cost reduction to the equivalent change in OFTO transfer value<sup>54</sup>. For simplicity it is assumed that the entire £34.1m contract-cost reduction relates to assets transferred to the OFTO, although in fact some of this amount relates to assets retained by the generator. The transfer value is calculated by adding factors such as interest during construction, insurance, construction management and overheads. These factors typically add about 33% to the contract cost. As a result, the £34.1m contract-cost reduction becomes a £45m change in the OFTO transfer value.

<sup>&</sup>lt;sup>53</sup> Based on the average of the 33kV and 66kV costs for OTM-to-OTM cables, less the £1.5m already included for OTM-to-OTM cables in the standalone option.

<sup>&</sup>lt;sup>54</sup> The Transfer Value is the Ofgem-calculated amount that the generator charges to the OFTO when the OFTO acquires their assets.

- ii) Conversion of the OFTO transfer value change of £45m into the change in the OFTO Tender Revenue Stream (TRS). The TRS is the basis for the tariff that the OFTO charges to National Grid and, for simplicity, it is also assumed to be the tariff that National Grid charges back to the generator. Examination of data published by Ofgem shows that the average TRS-to-Transfer Value ratio across recent projects is 7.5%<sup>55</sup> pa. Thus a £45m change in transfer value equates to a £3.4m pa change in transmission tariffs.
- iii) The hypothetical 500MW wind farm that this result is based on can be expected to generate an average of 2.1 million MWhr per annum. This is based on a capacity factor of 47%, in line forecasts for an "8MW-class" turbine<sup>56</sup>. The saving of £3.4m pa therefore equates to £1.7/MWhr.
- iv) As the original pricing data provided to GSR020 is at a 2015 price base (and other source data is for similar years) all of these calculated values, including the £1.7/MWhr value, are also at a 2015 price base.

<sup>&</sup>lt;sup>55</sup> Average for London Array, Lincs, Gwynt y Mor and West of Duddon Sands.

<sup>&</sup>lt;sup>56</sup> The Cost Reduction Pathways study indicates a capacity factor of 47.9% for an 8MW class wind turbine at a Round-3 site with 9.4m/s average wind. Siemens has confirmed that they are seeing estimated capacity factors at approximately this level for Round-3 projects.

Report into Lightweight Offshore Substation Designs