Power Take-Off System for a Subsea Tidal Kite

D5.1
Commercial Power System Design Report

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Internal Approval

Coordinator signature

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Powerkite
# Abbreviations/Acronyms

This list includes abbreviations used in the Powerkite project. Normally abbreviations are explained the first time they are used in the text.

<table>
<thead>
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<th>Abbreviation</th>
<th>Meaning</th>
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<tr>
<td>AEY</td>
<td>Annual Energy Yield</td>
</tr>
<tr>
<td>ALARP</td>
<td>As Low as Reasonably Practicable</td>
</tr>
<tr>
<td>DG</td>
<td>Deep Green</td>
</tr>
<tr>
<td>DG500</td>
<td>Deep Green 500kW/500V power plant</td>
</tr>
<tr>
<td>DNO</td>
<td>Distribution Network Operator</td>
</tr>
<tr>
<td>GBS</td>
<td>Gravity Based Structure</td>
</tr>
<tr>
<td>GVA</td>
<td>Giga Volt Ampere</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>LCL</td>
<td>Electronic filter (Inductor-Capacitor-Inductor)</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>MGS</td>
<td>Micro Grid System</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
</tr>
<tr>
<td>MVA(r)</td>
<td>Mega Volt Ampere (reactive)</td>
</tr>
<tr>
<td>OLTC</td>
<td>On Line Tap Changer</td>
</tr>
<tr>
<td>P_avg</td>
<td>Average Power</td>
</tr>
<tr>
<td>P_e</td>
<td>Electrical Power</td>
</tr>
<tr>
<td>PMSG</td>
<td>Permanent Magnet Synchronous Generator</td>
</tr>
<tr>
<td>P_{st}</td>
<td>Short Term Flicker Severity</td>
</tr>
<tr>
<td>P_{lt}</td>
<td>Long Term Flicker Severity</td>
</tr>
<tr>
<td>PE</td>
<td>Power Electronics</td>
</tr>
<tr>
<td>POC</td>
<td>Point of connection</td>
</tr>
<tr>
<td>PTO</td>
<td>Power Take Off</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SLD</td>
<td>Single Line Diagram</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>TDP</td>
<td>Touch Down Point</td>
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<tr>
<td>TMS</td>
<td>Tidal Marine Substation</td>
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</table>
Executive summary

A key deliverable of the PowerKite project was to develop a conceptual design of a complete offshore array system including substations, cables, and an on-shore grid connection. A base case array design was defined with focus on a short time to implementation, low cost, and implementing as many standard and proven technology solutions as possible within the array infrastructure. Relevant standards, regulations, and other requirements were identified, based on the assessment that it is an off-shore installation. Holyhead Deep off the coast of North West Wales was selected as a reference site.

The base case contains a floating Tidal Marine Substation (TMS) buoy solution. The design of the tidal power array was established and refined using modelling and simulations. Layout of electrical equipment, cable handling, and mooring solutions were studied and defined. The conceptual design was done in steps of 0.5-3-12-80 MW with low voltage (LV) generators.

As a variant, a base case design using medium voltage (MV) generators was studied with the same models.

As a second step, a series of different design cases were identified and studied, and an alternative design solution was developed based on sea-bed components.

The two alternative design cases are compared to each other within this report. This report concentrates on the electrical design aspects. Installation, service and maintenance procedures are discussed in more detail in Powerkite report D5.2 Commercial Service and Maintenance Strategy Report.

Kite output voltage is one of the main limiting factors for the design of the electrical power system. Higher voltage can be achieved in different ways such as using MV components (generator, converters) integrated in the kite or employing individual seabed step-up transformers for each kite or a combination of these options.

If an array system is to be built within a short timeframe, a buoy solution could meet all identified requirements. For future development a seabed solution based on individual seabed transformers and seabed switchgear units looks promising. Development of MV Power Take Off (PTO) for the kite would further improve the flexibility of the system and becomes increasingly important for higher unit power.

The variation of kite speed is creating power variations and these need to be minimized. In the base case a power variation of ±15% requires mitigation both by array design as well as design and control requirements on the kite generator.

The kite power that is used in the base case in this report is set to 500 kW, but higher capacity units are currently being designed outside of the project and the path forward is clearly towards increased capacity and higher export voltages. Therefore the two solutions reported here were later updated to study the impact of kite power as reported in Powerkite report D5.2 Commercial Service and Maintenance Strategy Report.
**Background**

One important goal of the Powerkite project was to develop a conceptual design of the complete offshore array system inclusive of the offshore system and onshore grid connection. The Holyhead site was chosen as reference site and, to the greatest possible extent, actual conditions and data was used. Holyhead is the site where Minesto intends to first implement the Deep Green technology in commercial scale.

It’s essential for the continued development to understand and find basic requirements for the design of an offshore electrical generator system to an onshore electrical network.

The Powerkite project was run in parallel with the DG500 project. The DG500 project spans the design, procurement, assembly, and operation of the first full-scale power plant in Holyhead Deep.

At present, the DG500 project does not include grid connection. The work covered in this report is the first attempt to make a basic design for the complete electrical system.
Scope

This task has produced designs of the entire tidal array power system inclusive of the PTO design, array components, and grid solution. Design cases were identified and classified according to various characteristics, notably the kite voltage and grid solution type. The array components and PTO system are first broken down into each component and discussed. This information is then used to build the design of the 80MW base case array proposal. The alternative cases identified are then compared to this base case system and also discussed and compared. An alternative seabed solution was subsequently developed.

The kite array control system was also studied as a part of the design work. To be allowed to connect the array power system to an onshore electrical power network there are a number of conditions which need to be fulfilled. Power variation caused by tidal stream variations, reactive power flow caused by long cables, voltage variations/flicker caused by the Kites figure eight flight, voltage variation caused by normal start and stopping of the site and more need to be controlled. The plant, the environment and the operating staff needs to be protected for any abnormal events which may occur. A high level description of the necessary array control systems (hardware and control strategies) for a grid connected tidal array was developed. For a number of defined operational modes and sequences, the applicable requirements were identified and possible control system designs to meet the requirements were listed. The requirements were derived from Grid Code, DNO requirements and relevant standards.
1. Background and Requirements

It was necessary to establish requirements for the power array system. Since Deep Green installation are not yet in commercial scale; relevant site and technology data was used, and assumptions are defined and established. The Holyhead Deep site off the North West coast of Wales was chosen as reference site and, wherever possible, actual conditions and locally collected data was used. Holyhead Deep is the site where Minesto intends to first implement the Deep Green technology in commercial scale.

The first part of this section describes the Deep Green principle and shows how the Power Take Off (PTO) chain was broken down to help structure the work. The second part first defines the Powerkite cases then expands to summarize maintenance and operational strategies for the different cases, describes the site conditions, identifies relevant standards and regulations, and introduces power and array control, SCADA, and system level design considerations.

1.1 Deep Green Principle

Deep Green is a subsea tidal kite which consists of a wing, carrying a turbine underneath, that is attached to the sea bottom with a tether containing load bearing rope and communication and electrical cables. The kite is steered in a predefined, 8-shaped trajectory as shown in Figure 1. The wing multiplies the velocity of the water flowing through the turbine using the same physical principle as a sailing boat that sails faster than the wind blows. This enables the converter to operate at lower tidal velocities than other technologies and use less material in construction in relation to installed capacity.

![Figure 1. Kite in 8-shaped trajectory](image-url)
1.2 PTO System Breakdown

The complete PTO system includes all parts that generate and transfer the electrical power. It is shown in Figure 2 for the base case and Figure 3 for the seabed solution. The turbine, gear box, generator, and (in these designs also) kite power electronics are integrated in the kite. The power is then transferred through the umbilical cable to a Tidal Marine Substation (TMS) or a seabed step-up transformer and, via a system consisting of cables and connection points, hubs, and export cable, to the grid.

While all parts of the electric chain need to be considered in the design, this report focuses on the design of the array power system and the power cables in the umbilical. The main PTO will be the generator, Power Electronics (PE), tether/umbilical cables, step-up transformers, and the array power system.

1.3 Array Components and PTO System Breakdown Structure

To create tidal parks with 3 to 80 MW capacity, generators are organized and interconnected in arrays. This section describes the main components in an array.

A breakdown of the Powerkite PTO system is included in Table 1 below. The array system is defined as PTO .5 to PTO .13; however, the array system cannot be developed independently of the generator (PTO .3), the PE in the kite, converters, and filters (PTO .4). They are part of the system and define key parameters, such as system voltage, and must be described at the same time.

<table>
<thead>
<tr>
<th>PTO .1</th>
<th>Kite</th>
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<tr>
<td>PTO .2</td>
<td>Turbine/Gearbox</td>
</tr>
<tr>
<td>PTO .3</td>
<td>Generator</td>
</tr>
<tr>
<td>PTO .4</td>
<td>Kite PE Control/Converters/filters</td>
</tr>
</tbody>
</table>
The Deep green principle can be applied for a kite of any size. For the array development in this project an applicable power range of 100 – 1500 kW is considered. Generators, converters, and filters available in the market are normally in the low voltage range, 500 – 690 V. This is especially true for components that are small and robust enough to be integrated in an underwater kite.

Transformers are heavy and as a result are currently not foreseen to be included in the kites; therefore, kite output voltage is limited by the generator voltage.

A low output voltage is a major limitation to the length of cables between the kite and the first transformer in the PTO chain, since cable losses will be high if the LV cables are long. Two ways to increase the freedom of design of the power array system is to either increase the kite output voltage or to introduce a transformer as early as possible in the chain.

The Powerkite project is addressing this issue, with development work targeting MV (1-3 kV) generators and multi-level converters.

When developing the base case design, the DG500 technical solution for the first prototype kite and umbilical is the basis. The basic characteristics of the electric design are described below. The base case electrical concept is included in Figure 4.

Power plant concept consists of a variable speed PM generator and back-to-back converters AC/DC – DC/AC in each kite. Kite output voltage is 500 V, 500 kW rated power in the base case for the Powerkite project. A summary of all powerkite cases is included in Section 1.4.
Figure 4. Base case kite electrical concept

All concepts evaluated in this report consider onboard power electronics, but there are other options available for various combinations of sites and kites for having the power electronics elsewhere, for example on shore.

### 1.3.2 PTO.5 Umbilical/Tether

The umbilical is the cable between the kite and the first part of the array, which is the TMS in base case and the seabed transformer the seabed case. It contains power cables for the transfer of the electric power generated, earthing wire, communication cables, and power cables for auxiliary systems at the bottom joint.

The umbilical is divided into two parts, with an interface at the bottom joint:

- The first part of the umbilical electrically connects the kite to the bottom joint and is contained within a protective core within the tether. The umbilical cable also extends into the kite.
  - It is a challenge to design an acceptable compromise between the size of cables and the size of the tether. Larger cables reduce electrical losses. The increase in the cross-sectional area of the tether increases drag and reduces the power produced.
  - The umbilical cable may be split into individual cables in order to have the most compact assembly.
  - Since the umbilical is integrated within the tether system for this part of the umbilical, these systems are often discussed together in the remainder of this report for the umbilical.

- The second part of the umbilical is from the bottom joint to the TMS. The umbilical originates in the bottom joint on the seafloor, before reaching the first component in the Power Array system, which could be in a buoy, on the sea floor or on a fixed installation depending on the Powerkite case. See Section 1.4 for a list of the Powerkite cases.
  - In the second part of the umbilical, the size and flexibility is less of a concern. To reduce overall losses, this part of the cables can have larger conductor area.
  - The umbilical is also protected to endure placement on the seafloor.
At the bottom joint interface, the umbilical may have connectors that enable disconnection and reconnection, or it may be a fixed joint.

Hybrid solutions are also considered, where the first part of the umbilical consists of individual cables with cross section optimised to available space and configuration in the tether fairing. In this part cable size and flexibility is determined by the tether design to reduce drag and ensure the correct operation of the kite.

### 1.3.3 PTO.6 TMS

The Tidal Marine Substation (TMS) is a device that integrates the major functions to collect power from a number of kites in an array. A Low Voltage (LV) switchgear connects the kites. It includes breakers and protections system that provides the possibility to disconnect individual kites either automatically in the case of an error to prevent damage to the rest of the system, or manually such as for maintenance on an individual kite. The LV switchgear is connected to a step-up transformer. A Medium Voltage (MV) switchgear is included after the transformer to allow control and disconnection of the MV network.

In the base case the TMS is integrated in a buoy, to allow easy access for maintenance.

### 1.3.4 PTO.6 Seabed Transformer

In alternative designs, as defined in 1.4, a seabed step-up transformer could be introduced as close as possible to the kite generator. The higher voltage allows for longer cable connections to the next unit.

### 1.3.5 PTO.7 Inter-Array Cables

MV Cables that connects a number of seabed transformers or TMS units to the next component in the PTO chain.

### 1.3.6 PTO.8 Seabed Switchgear/Sub-Hubs

In the PTO breakdown, seabed switchgears are used to connect the inter array cables and the export cables. It also includes breakers and a protection system.

There can be a number of levels of PTO.7 - PTO.8

### 1.3.7 PTO.9 - PTO.10 Hub Cables and Hubs

For large arrays, even a higher level of array structure could be considered by introducing switchgear hubs in various array configurations.

### 1.3.8 PTO.11 Export Cable

The export cable(s) connects the array to the POC on shore. To achieve redundancy, and to allow building a site in steps, several export cables can be used at a site.
1.3.9 PTO.12 POC

The Point of Connection (POC) refers to:

- Location of the physical connection point to the onshore grid
- Electrical grid properties at location point
- Grid requirements for connection of equipment at the connection point

The POC is an important parameter in studies of the design of the Array. For Holyhead, the final POC is not determined, and several options are under consideration.

To be able to perform basic electric calculations in Powerkite a model POC was defined. For these primary calculations, details for the on-shore connection was unknown and the grid connection was assumed to take place at a substation located directly at landfall of the export cable.

The POC at starting point was a virtual component, represented by a 100 MVA transformer. During the calculation work it became obvious that a virtual grid would be insufficient for yielding reliable results. Valid electrical data for a possible POC was supplied from Scottish Power, as a relevant grid owner, and the calculations were adjusted according to these new data.

1.3.10 PTO.13 On Shore PE

For the actual connection to the grid, an onshore substation will be built. It will include switchgears control system, step-up transformers from the array voltage to network voltage, production cable systems, and a connection to the DNO network.

1.4 Cases

There are several cases which are investigated and compared throughout the project. These are defined in Table 2 and further expanded upon in both Report [1] and Report Error! Reference source not found. Most of the project work is performed to establish and describe the base case, but there is also a seabed solution case.

- The base case is a grid solution where the TMS is a buoy
- The seabed case has where the TMS is split into transformer for each kite and hubs installed onto the seafloor

<table>
<thead>
<tr>
<th>Case</th>
<th>Array No.</th>
<th>Kite Power (kW)</th>
<th>Array Power (MW)</th>
<th>Voltage</th>
<th>Grid</th>
<th>Number of Kites</th>
<th>Cable Array Table</th>
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<tr>
<td>PK11</td>
<td>1</td>
<td>500</td>
<td>78</td>
<td>500V</td>
<td>Base case</td>
<td>156</td>
<td>1</td>
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<td></td>
<td>2</td>
<td>500</td>
<td>78</td>
<td>690V</td>
<td>Base case</td>
<td>156</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>500</td>
<td>78</td>
<td>3000V</td>
<td>Base case</td>
<td>156</td>
<td>3</td>
</tr>
<tr>
<td>PK2</td>
<td>4</td>
<td>900</td>
<td>81</td>
<td>690V</td>
<td>Base case</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1500</td>
<td>81</td>
<td>2200V / 3000 V</td>
<td>Base case</td>
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<td>5</td>
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<td></td>
<td>6</td>
<td>500</td>
<td>72</td>
<td>500V</td>
<td>Seabed Trafo + Hub</td>
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<td>6</td>
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<td></td>
<td>7</td>
<td>500</td>
<td>72</td>
<td>690V</td>
<td>Seabed Trafo + Hub</td>
<td>144</td>
<td>7</td>
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</tbody>
</table>
### 1.5.1 Maintenance and Service Strategy

The operational plans, maintenance strategies, and operational procedures for single kite installation, large scale kite array installation, TMS buoy, and seabed solutions are discussed in detail in Report [1]. The following section provides a strategy for the base case design.

Units in the Power system which includes but is no limited to the Kites, seabed switchgears, and TMS should be possible to disconnect individually to allow maintenance or reparation without impact on other components.

Kite maintenance is done on shore, the kite is recovered and replaced with another kite to reduce time and facilitate maintenance.

TMS buoy maintenance is performed at sea. TMS is electrically disconnected and bypassed during maintenance. TMS buoy is designed to allow replacement of all components (e.g. the transformer) at sea. Access is secured through a sufficiently large hatch. Detailed information on TMS maintenance procedures, operational requirements, and operational planning can be found in Report [1].

Service and reparation of seabed transformers and seabed switchgears are performed on shore. The component is recovered to the surface, replaced with an inventory component, and the component is transported to shore for maintenance or repair. Additional information on maintenance and inventory strategy can be found in Report [1].

### Seabed Case Deviations

A method for performing a physical lock-out procedure inside the seabed solution which fulfils the safety requirements to allow disconnection of kites and ensuring disconnection of the electrical system has not yet been developed.

The standard EN 50110-1 Operation of electrical installations, is one of the standards which may be applicable for this array system and contains content on operational procedures of electrical installations. There may be other similar standards have similar application. Standards are further discussed in Section 1.5.3. The standard EN 50110 covers three working methods:

- Working on dead system
- Working close to live system
- Working on live system

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**Table:**

<table>
<thead>
<tr>
<th>Kite</th>
<th>8</th>
<th>500</th>
<th>72</th>
<th>3000V</th>
<th>Seabed Trafo + Hub</th>
<th>144</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK3</td>
<td>9</td>
<td>900</td>
<td>72.9</td>
<td>690V</td>
<td>Seabed Trafo + Hub</td>
<td>81</td>
<td>9</td>
</tr>
<tr>
<td>PK4</td>
<td>10</td>
<td>1500</td>
<td>72</td>
<td>2200V / 3000 V</td>
<td>Seabed Trafo + Hub</td>
<td>48</td>
<td>10</td>
</tr>
</tbody>
</table>
The assessment is that the only acceptable method here is “work on dead system”. Several conditions need to be fulfilled before this method can be used:

- Disconnect the device/system from all live electrical sources.
- Check and prove that the device/system is dead.
- Apply earthing or short circuit tool to the device/system.
- Apply blocking/locking device to the disconnector/earthing switch, which is normally mechanically blocked.

The switchgear is inside a hull at 100 meters depth. Since the breakers, disconnectors, and earthing switches are electrically and remotely manoeuvred it is difficult to fulfil the requirements in the standard, as it is hard to imagine attaching a physical padlock to the disconnector and earthing switch or its control software. During maintenance of a subsea cable or subsea hub, the corresponding export cable may therefore need to be de-energized. Other standards and operating procedures may be more appropriate for a kite designed such that disconnection and connection to its subsea system is performed truly remotely by automated machinery. The applicability of EN 50110 for subsea kites is a subject that warrants further study.

### 1.5.2 Operational Considerations and Constraints

The following section contains a list of operational considerations and constraints, for in depth detail on operational planning and procedures please see Report [1]. A summary of consideration and constraints is included here:

- The proposed solution shall operate through the entire year and withstand all weather conditions.
- The proposed installations will ensure that all equipment is suitably supported, protected from any twist or bend or rotation, and minimize wear by reducing or removing contact. The relative motions of the support system and cables should be considered and addressed as required.
- All equipment shall have a minimum 25 year planned operational lifespan, with the following exceptions:
  - Batteries 5 years
  - Tether 5 years
- There should be solutions included for power supply in case of loss of connection to grid.
- All equipment shall be designed for environmental protection and zero risk attitude:
  - No oils or fluids, (i.e. dry type of transformers, air cooling systems, no diesel generators.)
  - Sealed batteries in UPS or other backup systems
- Relevant HAZID/HAZOP/Risk Assessments to be carried out and the results addressed within the design
- All risks involved in the use of the grid array system (including delivery, installation, maintenance, and de-commissioning) to be As Low as Reasonably Practicable (ALARP)
- Installations that require access by persons shall be designed for safe access.
- For the base case, common procedure for rescuing injured staff from electrical rooms shall be used. The injured person shall be able to be lifted from the rooms in the buoy, laying on a rescue stretcher in a horizontal position, all the way to open air. The hatches in the buoy are designed to meet these requirements and lifting equipment will be installed for the lifting procedure.
- For the seabed solution, there is no backup power supply in case of loss of connection to the grid:
  - The seabed solution does not include a UPS
  - Internal LV systems for power to auxiliaries are fed from the MV power cables so when the grid is lost these systems will be de-energized
1.5.3 Standards and Regulations

To be able to find and identify relevant standards, regulations, and other requirements some basic assessments has been made:

- The electrical array is an offshore installation. (Not a marine installation, which implies vessels and do not include fixed installations which are permanently connected to an onshore grid).
- The entire electrical system needs to follow general European requirements for offshore installations.
- Parts of the electrical system needs to follow specific British requirements as parts of the installation is assumed to be erected on British Islands.
- Parts of the electrical system need to follow specific Scottish Power Energy requirements as they have been chosen as a valid representative for the British onshore electrical network.
- The report is, at this stage, focusing on the electrical design so the design of dynamic and mechanical parts is not considered.

There are few standards, regulations, or guidelines which are directly addressing tidal turbines which are designed as this Deep Green kite; therefore, it has been necessary to find and identify standards and regulations which are used for similar equipment and systems.

- Report [2] contains an overview of the most important requirements and recommendations which affect the design and functionality from a net owner perspective.
- Report [3] contains a list of all relevant standards that were identified and implemented into the array design.

1.6 Site Description

Holyhead is the site where Minesto intends to first implement the Deep Green technology in commercial scale. More information can be found for site selection, array implementation within the selected site, and weather conditions and raw data collected for this site in Report [1]. The use of a real site also has the advantage that the results are relevant for one consistent set of inputs.

1.6.1 POC

For Holyhead, the final POC is not determined, and several options are under consideration, as shown in Figure 5.

To be able to perform basic electric calculations in Powerkite a “model” POC is defined. For these calculations, details for on-shore connection will be not be included, and the grid connection will be assumed to take place at a substation located directly at landfall of the export cable.

For the calculations, export cable length is set to 8 km.
1.7 Power and Array Control

There are several conditions which need to be fulfilled to introduce the kite power plant into an onshore electrical power network which are discussed in this section. The control systems and how to use them in the array to fulfill mandatory and operational requirements are described in Report [4].

The technology produces stable and reliable output power independent of the weather conditions; however, output power from the kite generator can vary for two main reasons:

- The tidal flows vary with ebb and tide. During a 24-hour period, two full cycles are passed. These cycles are comprised of four six-hour cycles with flow, and four slack water periods where the flow is very low. Kite is in standby mode for flows lower than approximately 0.5 m/s.
- The kite speed varies over the figure-8 shaped trajectory. Turning the kite costs energy and as a result the speed varies over the turns in the flight path. Since power output is a result of the cube of the kite speed, even small speed variations will give noticeable power variations.

These variances along with reactive power flow caused by long cables and voltage variation caused by starting and stopping the kite need to be controlled.

In the different array designs developed, the chosen solutions to fulfill the requirements are described, using the same structure as the Array control system report. See Figure 6 for a visualization of array operation modes and control sequences.
A Supervisory Control and Data Acquisition (SCADA) system is required to control and monitor the array, kites, TMS (Tidal Marine Substations), and the Distribution Network Operator (DNO) interface. Report [5] contains a schematic design and description of a SCADA system. The report shows how a SCADA system can be applied to monitor and control kites, array, and DNO interface.

The SCADA system will be used to merge all control systems into an overall operator control solution.

The array control systems consist of several components according to Figure 7, which includes:
The array control systems control and supervise switchgears all systems inside the onshore and offshore facilities. The array control systems are described in Report [4]. Below is a summation of the functions:

- The switchgear and auxiliary control system are used to monitor position and control of each individual breaker in the grid array. They are also used for supervision, to reset, and to cancel faults and alarms that may occur. Another purpose is to monitor power flow and voltage levels in the system.
- The power quality system monitors that consistent quality DNO demand by, for example, controlling kite output power and connection of shunt reactors.
- Kite pilot control system is used to control the amount of produced power delivered to the grid. It also controls the rudders which guide the kite in its flight pattern.
- The protection relay system checks if faults occurs at the grid and disconnect the faults.
- An emergency system stops kites and de-energizes malfunctioning parts. For more details see report [4].

Beneath all array control systems there are subsystems. Figure 8 shows the array control systems and a part of all subsystems which need to be included in the SCADA. Using a SCADA system all array control systems are interconnected and use the same HMI (Human machine Interface).
Inputs to the system array control systems will be signals from power plant operator, DNO operators, subsystems, and protection systems in the plant.

Figure 9 shows an example of an operator control room where the SCADA operator control is divided into two separate main HMI functions. Kite Pilot Control and Switchgear & Auxiliary control. The HMI functions are described in more detail in Report [4].

Figure 9 Operator workplace

1.9 System level Design Considerations

The system level design considerations are included in this section. Most of the considerations will apply to all cases, but the information which applies only to the base case or seabed case are clearly indicated.

1.9.1 Self-Safe Mode Capability

In case of disconnection from grid, or if the array is de-energized, all sub-systems must be able to be enter a self-safe mode. The emergency system is powered by the UPS in the TMS. Battery capacity is enough to keep systems alive for 48h. The emergency system consists of navigation lights, emergency lighting, and relay protection. Kites will have no power supply and go to self-safe mode.

1.9.2 System Voltages and Design

A concise list of system and design requirements follows:

- Kite generator: 500 VAC, IT-system with generator neutral point connected to earth via a high impedance
- Inter array voltage:
  - Base case: 33 kV AC
  - Seabed case: 0,5/24 kV AC
  - Both cases: star/delta system with transformer star point directly earthed on the LV side and open delta with the use of earthing transformer in the onshore substation on the MV side.
- Auxiliary supply:
  - Base case: 400/230 VAC, TN-system
  - Seabed case: Internal LV systems for power to auxiliaries are fed from the MV power cables
    - There is no UPS in this system so the protection relays needs to be powered by to the grid connected cables, meaning an internal LV system which is supplying the protection relays and the switchgear manouevring system instantly as soon as the MV cables are energized. When the connection to the grid is lost it is not possible to operate any device in the switchgear or to monitor any parts, status, or events.
As the distance to the onshore substation, and nearest LV supply, is no less than 8000 meters, it’s not possible to use a LV auxiliary supply for the protections relays or the switchgear devices.

- Export cable:
  - Base case: 33 kV AC
  - Seabed case: 24 kV AC
- On shore DNO HV system, transformer direct earthed

### Earthing Strategy

The need of a dedicated earthing conductor in the umbilical power cable was investigated. A summary is provided below, and the full earthing strategy is described in Report [6].

Earthing requirements are dependent on the type and design of the electrical system.

- An island system, meaning a marine system that is not connected to an offshore electrical system, may use a wet earthing system where the sea water is used as an earthing conductor.
- An offshore system, meaning a system that is connected to an onshore electrical system, needs to consider the requirements which are valid for the offshore and the onshore systems, as a combined and interconnected system.

For a future industrial scale implementation of this project, a dry cable earthing system comprised of a protective earthing conductor across the entire system shall be used for reasons listed below. The earthing conductor/screen continuity will be maintained across each joint/connector and will be directly connected to earth terminations at the onshore substation and at each electrical device.

- Relevant standards state that a dedicated protective earthing conductor shall be used to ensure that the electrical safety is guaranteed without exception.
- The earthing conductor shall be directly connected from the generator’s earthing terminal to an earthing system which shall be designed to withstand the earth fault currents which may occur.
- The use of the sea water as a reliable earthing conductor is not considered as an option.
- The British or the Swedish Electrical Safety Regulations may not be valid for offshore plants, but the content aligns with the DNV Offshore Standards that any electrical system shall be designed and constructed according to good safety practice, which includes the implementation of an earthing wire.
- The PTO design report from Schottel is showing the connection point of the earthing wire which shall be included in the umbilical power cable.
- The metering system in the PTO will not work without its neutral point connected to the earthing conductor.
- It will be possible to connect harmonic mitigating wires to the earthing conductor which may reduce disturbances and malfunctions in electronic equipment and by that follow the requirements in the standards.

### Electrical Protection System

A 500 VAC is used for the base case prototype.
In this section a design proposal of a protection arrangement for an 80MW LV/HV array with tidal generators connected to a DNO HV System is described.

![Figure 10. Relay Protection Arrangement for an LV/HV Generating array Connected to a DNO HV System](image)

A relay protection coordination must be implemented for each tidal array system site. The generator and the DNO protection settings will be designed so the protection system will operate in a selective way disconnecting the part, or parts, of the system which is nearest the fault and allow the rest of the system to operate as normal. A relay protection arrangement is shown in Figure 10.

Some protection requirements for the onshore part are listed below:

- **Earth Fault Protection**
  - The earth fault protection in the onshore switchgear must be coordinated and agreed with the DNO. Because of the delta winding on the step-up MV transformer an earthing transformer is introduced to build up a point for measure of zero-point currents to be able to protect the system from earth fault. The earthing transformer is also equipped with an LV winding supplying the auxiliary load. The earthing transformer is equipped with an earth fault protection disconnecting the busbar MV incoming breaker, HV power back up breaker, the T2 33kV breaker in the TMS1, and the 33kV breaker against TMS2 in the TMS1 when a fault occurs.

- **Directional Short circuit protection**
  - The 33kV Switchgear is equipped with directional short circuit protection at the incoming breaker to protect the switchgear from short circuits. The three HV CB breaker against the...
Kites are also equipped with directional short circuit protection in the export cable to protect the export cables from short circuits.

Some protection requirements for the offshore part are listed below:

- **Earth Fault Protection**
  - Earth faults in the TMS and umbilical are detected in the Earth fault protection unit measuring the zero-point current in the T2 transformer. Earth fault in the generator and cables between the converter and the generator is protected by an internal Earth fault protection inside the kite and disconnecting the generator breaker inside the kite.

- **Directional Short Circuit Protection**
  - The 500V Breaker between transformer and the bus has a busbar protection.

- **Differential Protection**
  - The transformer has an ordinary transformer protection with differential protection.

- **Low Voltage Protection in TMS and Kites**
  - Each kite LV switchgear breaker in the TMS is equipped with short circuit, over voltage, under voltage, over frequency, under frequency and reverse power protections, all according to the grid code.

To avoid damages caused by switching transients and lightning strokes, surge arresters will be placed at the LV generator cables termination points in the LV switchgear and at the MV export cable termination point.

Each kite generator power system includes a protecting system for over current and short circuits in the umbilical and a current limiter in the converters to protect the converters and the cable system. The kites also require an earth fault protection to protect the generator, converter, and cable between the generator and converter from faults. This protection system is designed to monitor the current between the star-point in the generator and the earthing point.
2. Design of a Base Case Power Array System

The strategy for array design was to develop a concept solution detailed enough to assess key parameters which include, but is not limited to: electrical efficiency, protection systems, fulfilment of requirements from network owners, and cost while minimizing design complexity. A base case system was designed with focus on short timeline to implementation, low cost, and implementing existing and standard technology wherever possible. Alternative and improved designs were to be investigated relative to the base case design.

The base concept design was first developed as 6 kites (3 MW), connected to one TMS. A floating buoy solution was chosen for the TMS in the base case design. The 3 MW base case solution was further detailed with respect to earthing and protection systems and extended to cover a full array of approximately 80 MW. Detailed modeling of the base case was done with the tool EMTP-RV and the model was used to evaluate different designs and develop the solution.

The conceptual design was done in steps of 0.5-3-12-80 MW with low voltage (LV) generators. Alternative designs using 3 kV medium voltage (MV) generators were also studied with the same models. See Figure 11 for array design steps.

![Array design steps](image)

An alternative solution using seabed components was developed and is described later in the report in Section 4.

2.1 Design of the 3 MW Array

The initial kite design proposal has a low voltage output of 500 V. Each kite would be connected to the TMS with the LV (500 V) umbilical cable. The TMS contains a 3.16 MVA stepup transformer 500 V to 33 kV and is connected to the onshore grid substation via a 33 kV export cable (see Figure 4). The connection with the local onshore distribution network is via an 132/33 kV transformer within the onshore substation. The detailed design of this onshore substation is not within the scope of the project but required data has been collected from local network owners representing a future possible substation, and some requirements on the substation were identified. The initial sub-array design is shown below in Figure 12.
A sub-array configuration comprising 6 kites connected to the TMS and then to the onshore grid via an export cable was considered as basic array configuration and the building block for the future industrial array as shown in Figure 13. Single line diagram (SLD) of this basic array was used as a starting point for modelling and redesign and then expanded to more complex layouts.

**2.2 Electrical Calculations**

As part of the design phase electrical calculations were made to verify if the proposed design was able to fulfill project requirements which include, but are not limited to, grid standards, technology components requirements, and cost.

Calculations were executed such as:

- Losses
- Short circuit current
- Earth fault current
- (Rough estimate of voltage fluctuations and flicker)
- Reactive power flow
- Power cables capacity
- Overall efficiency

The modeling software used to analyse the electrical behaviour of the array was EMTP-RV. The 6 kites in the sub-array were represented by PQ nodes for the load flow analyses, but they were not represented for the fault current analyses. Their contribution to the fault current was estimated.

The first step was to perform quasi-dynamic simulations (series of load-flows) in which the production fluctuation due to the kite 8 shaped trajectory, an example is shown in Figure 14, was taken into account. This enabled assessment of the efficiency of the transmission chain with a loss calculation as well as the voltage profile along the transmission chain; in addition, it gave an opportunity to assess components of the initial powertrain design proposal (cables, transformers, etc.) and iterate with several alternatives to reach better or optimal solution. The low voltage umbilical cable linking the kite(s) and the TMS are good examples as discussed in the section below.

![Figure 14. Example of simulation of the production of 1 kite in one load point (350 kW), together with sinus approximation.](image)

### 2.3 Design Iterations

The umbilical cables are passing through the specially designed tether that connects the kite to the seafloor. One major challenge was to find an acceptable compromise between the size of cables and the size of the tether. Larger cables reduce electrical losses but increase the tether size (cross section area) which creates additional drag and reduces the power produced.

Several alternatives for the LV umbilical cable have been considered in order to reduce electrical losses while accommodating the power cables within the tether:

1) In the first alternative the LV umbilical cables are composed of 4x50mm² conductors per phase (in total 200 mm² per phase) for a length of 500 m. The use of 4 conductors per phase allows for more physical flexibility of the cable (e.g. lower stiffness). This solution proved to be inefficient as losses in the umbilical were, on average, 10% of the production.
2) Increasing the total cross section to 280 mm² over the full length of the umbilical LV cable (500 m) did not lead to a significant reduction in electrical losses, but increased cable weight and size which is negative for the operation of the tidal kite.

3) The third alternative was to split the LV umbilical cable in two parts: first a 100 m cable ‘flying’ part in the tether with the smaller total cross-section of 200 mm², followed by a 400 m cable laid on the seafloor and with a much bigger total cross-section (740 mm² per phase) in order to lower electrical losses. With this solution, the losses were reduced to 7% of the production.

4) Alternative design work of the umbilical cable continues and is focusing on a higher voltage level or the use of DC cables.

In addition to studying umbilical cable alternatives, other nominal voltage outputs of the kites were simulated (1.1 kV, 2.2 kV, 3.3 kV); as expected, the array presents a better performance with higher nominal kite voltage. The Powerkite project also included design of a medium voltage generator and converters for the kite.

Modeling identified design limitations of the kite and transmission chain that would restrict the compliance with the local network requirements; the power factor at the point of connection to the grid wasn’t always within the specified limitations. Several solutions to this issue were considered. A first option is to install reactive power compensation units or use the kites to manage the reactive power.

The kite(s) power production variation of 15% around the average production value results in fluctuations in the output voltage level that are outside of required limits (flicker issues). This needs to be addressed. One way is by phase-shifting the power production from kite to kite in order to control the fluctuation of the array output. In the load-flow simulation of the 6-kite array, several phase shifts have been considered. A phase shift of 60° between the kites allows smoothing of the power exported to the grid, although the power and voltage fluctuations remain the same at the kite output. Another option is to use an online tap changer at the power transformers. More detailed quantification of flicker emissions and start-up voltage fluctuation is ongoing.

The second step was to proceed with short-circuit simulations, in order to assess the adequacy of the circuit protections and thus the assets safety. This exercise resulted in proposal of mitigation measures for very low fault current that might be difficult to detect by the overcurrent protections. The mitigation measure was to adapt the section of the earthing wire in the LV cable. The result was a larger cross section of the earthing wire which allowed for higher fault currents that could be more easily detected.

2.4 Design of the 80 MW Array

The results from the 3 MW simulations input into the design options for larger arrays at the reference site. Several options for the configurations of the full-scale array were studied with one choice considering the division of kites in 3 parallel export strings and thus export cables as shown in Figure 15.

The strings are composed of up to 9 TMS in a daisy chain, each TMS connecting 6 kites. The cross-section of each MV cable connecting the TMS is adapted to the cable location, considering that cables closer to the onshore substation will require higher capacity.
In the simulation of the full array the switch was made from 50 MVA to 100 MVA transformer at the onshore substation. The cross-section of the export cable between the onshore sub-station and the closest TMS is 400 mm$^2$.

In the event the export voltage from the kite is increased, the buoys could be made slightly larger and accept more cables, and thereby reducing the number of buoys in the system. This has not been included in the report.

The modeling software EMTP-RV was again used to analyse the electrical behaviour of the full array. The 156 kites were represented by PQ nodes for the load flow analyses; however, the fault current analyses were represented by three-phase voltage sources behind a short-circuit impedance. This allowed to take into account their contribution to the fault current, considering that their contribution was not negligible as was assumed for the 6 kite array.

The modelling of the 80 MW base case, including the load flow, short circuit, and flicker calculations on the 80 MW array is described in more detail in a separate report.

The following conclusions can be drawn from the modelling for the 500C generators:

- Umbilical cable of 4 parallel 50 mm$^2$, including an earthing conductor, results in high losses.
- Hybrid umbilical cable of 4 parallel 50 mm$^2$ and 4 parallel 185 mm$^2$ reduces the losses.
- 50 mm$^2$ cross section is on the limit and is the main source of losses. Losses may be slightly higher with PF compensation for voltage variations.
- A shunt reactor is needed for compensation of the capacitive reactive power which is created by the power cables.
- An On Line Tap Changer (OLTC) is needed to keep the system voltage level within required limits.
- Kite speed, and thus power production, varies over the trajectory (+/- 15%). This power variations result in voltage variations both at the kite and at POC.
  - The proposed mitigation for POC variation is to implement a 6-kite grouping with phase shifting between each kite.
The varying power also means that converters in kites need to have the possibility to control the active/reactive power ratio to reduce voltage variations at the kite. The array control system should set a requested power factor for each kite:
- A larger umbilical cable cross section would reduce the voltage variation problem at the kite.
- If power variations due to speed are higher than the +/-15% assumed here, this problem becomes bigger.

As an option to the 500 V generator system a 3 kV system was studied to find out if this was a feasible and recommended alternative. The calculation and modelling were focusing on the electrical losses comparing the LV and MV alternatives. No short circuit or earth fault modelling were performed for the 3 kV alternative but was replaced with a simplified calculation. The 33 kV array system was the same as for the 500 V so no new calculations were needed for the MV array.

Summary and conclusions of the calculations of the 3 kV option:

- The 4 parallel LV umbilical cables were replaced with 1 MV cable of 35 mm² in its full length of 500 meters.
- The TMS transformer was adapted to this option, 3 kV to 33 kV, using the same data as the base case 500V transformer.
- The generators short circuit impedance was recalculated to fit the 3 kV option considering the generator system limitation of 1kA short circuit current at 3 kV.
- Only load flow analyses were performed using the calculation model.
- Short circuit and earth fault currents in the umbilical cable were checked in a simplified calculation.
- The transmission efficiency is increased using 3 kV mostly due to less losses in the umbilical cable.
- The voltage level at the kite generator is always between 0.9 and 1.13 per unit of nominal voltage with the 3 kV model. This result is better than with the 500 V, but the maximum limit of 1.1 per unit is still exceeded. The same options mentioned for the 500 V model could be used to tackle this issue.
- The conclusion concerning the power factor at POC is similar as for the 500 V model.
- The rated current for the 35 mm² umbilical cable was not exceeded.
- The conclusion concerning the currents in the MV cables are similar as those provided for the 500 V model.
3. Array Description for 80 MW Base Case

In this report the 80 MW base case solution is described.

3.1 Array Size and Structure

The array consists of 156 kites, connected via 26 TMS in three separate chains, connected to shore with three export cables.

This array design is based on the 3 MW sub-array of 6 kites connected to one TMS as shown in Figure 16. 9 of these sub arrays are connected in a daisy chain arrangement forming a 27 MW unit that is connected to shore via an export cable. Two 27 MW and one 24 MW chains are connected to shore with three export cables to form the full array as shown in Figure 17.

Nominal power is 78 MW but is referred to as 80 MW for simplicity. All TMS are identical, with integrated Sub-hub allowing connection to the next TMS in the chain. The structure and size of the array is limited by the length of the LV cable. The losses and impedance of the 500V cable are limited by placing the kites around the TMS with approximately 500m long umbilicals. Inter-array cables are designed for actual load, i.e. not identical, as the power is accumulated along the chain. The single line diagram for the 80MW base case can be found in Figure 18.
Figure 18. Single line diagram for 80 MW base case
3.280 MW Base Case Components

3.2.1 Kite Generators

Variable speed PM generator with back-to-back converters AC/DC – DC/AC in each kite.

Kite output voltage is 500 V, 500 kW rated power

Identified key requirements related to kite, and array, design:

- Voltage at kite output to be controlled within 90 – 110%.
- Kite must withstand grid disconnection at 100% load
- The kite, as individual generator system, must be able to start and stop production smoothly and in synchronization with the grid, without large step voltage changes. The setup of the kites in the base case, as variable speed generators with back-to-back converter enables this. Fixed speed generators would need special synchronization devices.

3.2.2 Umbilical Cable / Tether

As introduced and discussed in Section 1.3.2 the umbilical cable is a hybrid umbilical with two parts;

1. Tether part with four individual three-phase power cables and FO cable integrated in the protective tether fairing. Conductor cross section is a compromise between electrical losses and available space in tether. 4/50mm² cables.
2. Umbilical part, with four individual three-phase power cables and FO cable integrated in an umbilical cable. 400 m long. Cross section is chosen to minimize losses and impedance. 4/185mm² cables

The two parts are joined together with a fixed joint after the bottom joint. The umbilical is integrated with the tether and bottom joint in an assembly that is handled as one unit. Figure 19 shows this design, and Figure 20 shows the cables and connectors between the kite and the TMS. Note that the tether profiles are preliminary design examples and not indicative of what would installed.
The maintenance and repair strategy is based on recovering and replacing the kite. The kite will be disconnected at the top joint during recovery, requiring easily detachable connections for power cables and signal cable. The requirements of this operation are included below in Table 3. Recovery will be done above sea surface, enabling use of Dry mate connectors.

### Table 3. Top joint connection

<table>
<thead>
<tr>
<th>Functions (PTO.5)</th>
<th>Comment/Design Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umbilical cable (tether) detachable from kite</td>
<td>Easy disconnection at kite recovery. Water tight (10 Bar) 25 year life Circa100 disconnection/connection</td>
</tr>
</tbody>
</table>
There are commercially available connectors that can be used, as shown in Figure 21.

![Dry Mate Power connector and Dry Mate Optical connector](image)

Figure 21. Examples of connectors for umbilical

The kite is assumed to be connected to the tether at the top joint in this report but other design options exist.

### 3.2.4 Bottom Joint

For the array power system study, the bottom joint is only a physical connection with two parts. In the base case the umbilical cable is only connected to detachable part of bottom joint, i.e. a permanent cable joint is feasible.

### 3.2.5 TMS Cable Connections

The umbilical cable must allow off shore installation and detachment from the TMS buoy. Electrical connections at TMS are fixed installation in switch gear. Cable hang off and protection is described in the following TMS section.

### 3.2.6 TMS

The TMS buoy collects electric power input from 6 kites and transforms to 33 kV output. The buoy also contains a sub-hub, which is a high voltage switchgear that is used to connect to the two adjacent TMS buoys.

In addition to the transformer and LV/MV switchgears the TMS also includes:

- Uninterruptible Power Supply (UPS) solution
- Fans, small power installations, and other small components
- Equipment for cable connections
- Communication equipment
- Auxiliary power equipment

Figure 22 shows a SLD of the TMS and a sub-hub for connecting to the next TMS. Table 4 contains a description of TMS functions.
### Figure 22. Single line diagram for TMS and Sub-Hub for Base case

<table>
<thead>
<tr>
<th><strong>TMS functions</strong></th>
<th><strong>Status</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Connect kites and collect electrical power</td>
<td>Connect up to 6 kites</td>
</tr>
<tr>
<td>Electrically disconnect individual kites to enable</td>
<td>Individual breakers (QA1)</td>
</tr>
<tr>
<td>recovery for service or in case of electrical fault</td>
<td>Individual disconnection/bypass for each kite</td>
</tr>
<tr>
<td>Transform from kite output voltage to inter-array</td>
<td>500V → 33kV</td>
</tr>
<tr>
<td>voltage</td>
<td>Max 3.1 MW</td>
</tr>
<tr>
<td>Power supply to kites in standby, such as during slack</td>
<td>Power supply from grid</td>
</tr>
<tr>
<td>turns</td>
<td>3kW/kite; total 18 kW</td>
</tr>
<tr>
<td>Emergency power for TMS via UPS</td>
<td>Simple UPS for 24h/0.5 kW /11 kW h for emergency power and protection relay</td>
</tr>
<tr>
<td>lights and protection relay system</td>
<td>system considered</td>
</tr>
<tr>
<td>Backup power supply from a maintenance ship</td>
<td>Suitable LV plug-in system</td>
</tr>
<tr>
<td>Collect power from next TMS (sub-hub)</td>
<td>1 input slot 33kV</td>
</tr>
<tr>
<td></td>
<td>10 TMS can be connected in series</td>
</tr>
<tr>
<td></td>
<td>Switchgear handles up to 36 MW</td>
</tr>
<tr>
<td>Export electrical power to sub-hub or export cable</td>
<td>1 output slot 33kV</td>
</tr>
<tr>
<td>(sub-hub)</td>
<td></td>
</tr>
<tr>
<td>Electrically disconnect and bypass TMS in case</td>
<td>TMS bypass breaker for repair/service</td>
</tr>
<tr>
<td>of electrical fault or array maintenance and repair</td>
<td>breaker (QB1)</td>
</tr>
<tr>
<td>(Sub Hub)</td>
<td></td>
</tr>
<tr>
<td>Climate control to protect components</td>
<td>Climate control system included</td>
</tr>
<tr>
<td>Provide power to kites for X hours in case of</td>
<td>No UPS to keep kites in standby included</td>
</tr>
<tr>
<td>disconnection from grid via UPS</td>
<td>UPS would need to be very big</td>
</tr>
</tbody>
</table>

Table 4: Functional description of TMS
3.2.7 TMS Buoy solution.

In the Base case the TMS is a Buoy solution with integrated Sub-Hub. As can be seen in Figure 23 the dimensions for the cylindrical buoy are as follows:

- Diameter 8m (12 m with cable protection)
- Height 17.5 m (5 m above sea level)
The dry weight and buoyancy of TMS buoy, as seen in Table 5, are as follows:

- Boy hull: ~90 ton
- Boy with electrical components: ~110 ton
- Boy with all components + free hanging mooring lines and umbilicals (from sea bed to attachment in TMS buoy): ~160 ton
- Buoyancy: ~10 ton
As seen in Figure 23, all electrical control equipment is placed on the upper deck (-1 deck) and the lower deck (-2 deck) is used to house cables and cable trays. Underneath the lower deck there is a space for stiffeners which transfer the mechanical load between the buoy hull and the lattice structure. The ballast base is a cylindrical steel box which can be filled with ballast weights such as steel or concrete. The ballast weights are used to trim the Center of Gravity (COG) as well as the buoyancy.
There are items which haven’t been designed in detail which will be housed in the buoy. Some of these components will be designed in detail such as the 6T crane. Standard components like cable hang off, cable trays, and navigation aids can be provided by suppliers. Complex components such as climate/cooling system can be left out in the first stage, provided a dedicated space in the buoy is reserved for it.

The buoy is accessible for service and maintenance through the two hatches, one in the weather deck and another between upper and lower deck. The hatches are 3.8m x 1.6m which is enough to enable installation of the electrical equipment. The hatches also have man holes, which allow access for crew. There is a ladder between all decks. The TMS buoy is shown below in Figure 24.

The umbilical run in an I-tube, which is a pipe attached to the buoy hull, on the outside of the buoy to achieve a simpler installation as well as cable protection; furthermore, there is a lattice structure which serve as cable protection. All cable entries are well above the sea level.

TMS Mooring and Umbilical Arrangement

The three-legged mooring system (marked with blue in Figure 25) is an individual system with separate anchors. Each mooring leg consists of a mooring line, clump weight, ground chain, and mooring anchor. The mooring line is a polyester fibre rope taut leg riser with a bridle connected at upper and lower pad eyes on the buoy lattice structure as shown in Figure 26. The bridle is necessary to reduce buoy motions. Polyester ropes are corrosion proof and have a high fatigue life as they are always under tension. A clump weight with a submerged weight of 117 tons is required at the chain-rope connection to resist the vertical component of the load. The clump also prevents clash between kite and mooring line, since the kite might collide with the...
mooring if directly attached to one anchor. The mooring anchor is a drag embedment anchor which resists the horizontal component of the mooring force.

Figure 25. Top view of array with TMS, surrounded by 6 kites

The option of using the kite foundations to moor the TMS was investigated; however, that option was ruled out when it was determined that the Gravity Based Structure (GBS) may not be able to also moor the TMS buoy unless the foundations are increased in submerged weight and designed to resist the additional (horizontal) load from the buoy. The following points further indicate that separate mooring anchors are preferred for the TMS buoy:
Certain potential advantages with separate anchor, compared to the use of the GBS:

- More flexibility in placement of TMS buoy anchors, with regards to buoy motions and seabed conditions. By using a separate anchor for the TMS horizontal restraint, it can be set in the correct heading towards the buoy without impacting on the performance, position or heading of the kite tether foundation.
- More flexibility in design of mooring system.
- Shorter Kite-TMS umbilical’s, 400m instead of 450m (see Figure 27).
- The installations of GBS and TMS buoy are not linked and can be carried out independently.

The moorings need to be pre-tensioned during installation. They also require re-tensioning during the service life of the system, because the ropes will exhibit some elongation over time. A mechanism for this can either be fitted subsea at the mooring system or be integrated in the buoy. The selected option is a short adjustment/pre-tensioning chain and subsea chain adjuster at the lower end of the polyester rope. The tension is applied by a vertical pull from a surface vessel with a subsea connection to the adjustment chain.
3.2.8 Umbilical

There are six Kite-TMS umbilicals (marked with yellow in Figure 25). Each one runs horizontally on the seabed from the GBS to the Touch Down Point (TDP) to prevent clash between umbilical and kite. To prevent a clash between the umbilical and the mooring and other umbilical, there is an angle of 30 degrees between the lines (see Figure 25). The umbilicals have also been designed to withstand fatigue.

All Kite-TMS umbilicals are run in the same pattern to result in similar cable lengths. Typical umbilical length kite-TMS for a soft catenary shape is 400 meters: $125 + 125 + 150 = 400m$. A Lazy-s shape require a slightly longer cable, but well below 500m.

![Figure 27. View of array, only one kite (out of six) is displayed](image)

The TMS-TMS umbilical and the TMS-Land umbilical (marked with red in Figure 25-9) are run similar to the Kite-TMS umbilical from buoy to TDP, described above. From the TDP these umbilicals are run horizontally on the seabed towards the next TMS or land.

![Figure 28. Side view of mooring and umbilical arrangement with a Lazy-s system](image)

An umbilical overlength is required to prevent that the umbilical is stretched when the buoy moves. This can be solved either by a soft catenary shape (see Figure 26) or a Lazy-s system (see Figure 28). The exact geometry will depend on the cable design and its construction, as well as its behaviour in the water column and interaction with the seabed; as a result, the decision of which option to choose depends on the site conditions.
The simplest option is the soft catenary where the umbilical is free hanging. This requires less components and results in a shorter umbilical length. A Lazy-S system is more complex but gives the advantage of restricting and controlling the umbilical movements.

TMS Buoy Installation

It may be desirable to have the TMS buoy moorings in place and the buoy on site prior to installing the GBS and umbilicals, so that the umbilicals can be hooked up to the buoy as soon as they are installed. The installation of the TMS Buoy Concept is presented, starting with the mooring system.

Installation of the mooring system could be by anchor handling vessel capable of 130 tonnes bollard pull, taking an estimated day per anchor leg plus a day for hook-up and pre-tensioning. A typical installation sequence could be as follows:

1. Deploy and install the anchor using bollard pull from a suitable vessel or applying tension by some other means, such as subsea tensioner or deck-mounted winch.
2. Lay the ground chain towards the mooring pattern centre.
3. Connect the adjustment chain and subsea chain adjuster to the clump weight before it is deployed.
4. Connect the clump weight to the ground chain end and deploy it overboard towards the seabed, keeping the ground chain tight throughout.
5. As the clump weight is lowered, pay out the adjustment chain and chain adjuster.
6. Connect the polyester rope to the adjustment chain and continue lowering the system to the seabed.
7. Land the clump weight on the seabed with the ground chain pulled tight between the anchor and clump.
8. Lay the adjustment chain and adjuster on the seabed away from the clump weight.
9. Continue to pay out polyester rope until the end is about to go overboard.
10. Connect the polyester bridle to the polyester riser rope and attach the bridle to the buoy.
11. Alternatively, the polyester bridle and mooring rope may be connected to the buoy first, then connected to the pre-laid adjustment chain end.

There are two options of how to install the umbilical, both require two Multicats with cranes and winches and a RHIB to transport crew. In Option 1, the umbilical is laid in one operation starting from GBS/land/other TMS. The umbilical is onboard a vessel on a reel and the TMS buoy has a winch on deck with a messenger line. A typical installation sequence could be as follows:

Umbilical installation – Option 1

1. Lay umbilical, starting from GBS/land/other TMS
2. Lay subsea equipment attached to umbilical (bend restrictor, Lazy-S system etc.)
3. Vessel approach TMS buoy
4. Retrieve messenger line from TMS buoy
5. Connect messenger line to umbilical onboard vessel
6. Winch on TMS buoy pays in umbilical
7. Umbilical fits through the I-Tube

In Option 2, a connector is added to the umbilical splitting the lay into two shorter operations. One end of the umbilical is pre-fitted to the TMS buoy and is on a reel onboard the deck of the buoy.

Umbilical installation – Option 2

1. Vessel approach TMS buoy
2. Move umbilical reel to vessel deck with the vessel’s crane
3. Lay umbilical, starting from TMS buoy
4. Lay subsea equipment attached to umbilical (bend restrictor, lazy-s system etc.)
5. Pay out umbilical towards GBS/land/other TMS
6. Leave connector on seabed connected to surface buoy
7. The other end of the umbilical is laid from GBS/land/other TMS
8. The connector is picked up from the seabed and umbilical is connected
9. Connector is lowered to seabed

Option 2 might be preferred in an installation perspective due to the split into two shorter operations, resulting in better utilisation of vessels and crew, smaller weather windows and lower costs; however, the disadvantage is a slightly longer umbilical and an additional connector which might result in electrical losses.

3.2.9 Sub-hub, Inter-Array Cables, and Export Cables

There are different types of subsea cables regarding design, the intended use, installation technique, voltage levels, and other inputs. The base case, and the seabed solution, is focused on MV cables which are installed at the seafloor with no anchor weights. In addition to the power transmission, the cable also contains fiber optic cables in order to establish communication between the array devices and an onshore supervision system. The power cables need to be very robust, heavy enough to be fixed at the seabed, but possible to install using common installation technique. The choice of cable type has been discussed with experienced installers and following their recommendation 3 phase MV cables with double steel armor have been chosen.

Please find an example of a subsea cable in Figure 29 below.

Figure 29. Subsea cable figure
Inter array cables and export cables specifications and size are summarized in Figure 30. In this table, all TMS cables are 1000, except the cables W101, W110, W1109 which are the export cables to shore and are 8000 m long.

<table>
<thead>
<tr>
<th>Wire number</th>
<th>Type</th>
<th>Size</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>W101</td>
<td>XLPE 36 kV</td>
<td>1x3x400 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W102</td>
<td>XLPE 36 kV</td>
<td>1x3x300 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W103</td>
<td>XLPE 36 kV</td>
<td>1x3x240 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W104</td>
<td>XLPE 36 kV</td>
<td>1x3x185 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W105</td>
<td>XLPE 36 kV</td>
<td>1x3x185 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W106</td>
<td>XLPE 36 kV</td>
<td>1x3x120 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W107</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W108</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W109</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W110</td>
<td>XLPE 36 kV</td>
<td>1x3x400 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W111</td>
<td>XLPE 36 kV</td>
<td>1x3x300 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W112</td>
<td>XLPE 36 kV</td>
<td>1x3x240 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W113</td>
<td>XLPE 36 kV</td>
<td>1x3x185 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W114</td>
<td>XLPE 36 kV</td>
<td>1x3x185 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W115</td>
<td>XLPE 36 kV</td>
<td>1x3x120 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W116</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W117</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W118</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W119</td>
<td>XLPE 36 kV</td>
<td>1x3x400 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W120</td>
<td>XLPE 36 kV</td>
<td>1x3x300 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W121</td>
<td>XLPE 36 kV</td>
<td>1x3x240 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W122</td>
<td>XLPE 36 kV</td>
<td>1x3x185 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W123</td>
<td>XLPE 36 kV</td>
<td>1x3x185 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W124</td>
<td>XLPE 36 kV</td>
<td>1x3x120 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W125</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
<tr>
<td>W126</td>
<td>XLPE 36 kV</td>
<td>1x3x95 mm²</td>
<td>Steel armored sub sea cable</td>
</tr>
</tbody>
</table>

Figure 30: Base case inter-array cables
Export cable options have not been studied in detail. Three export cables were chosen to give redundancy and allow for a stepwise buildup of the array. If advantageous, such as to reduce installation costs, one option would be to install all three export cables at the same time.

Export and inter array MV cables are assumed to be installed without anchor weights along the cable routes but a double steel armor design is recommended to prevent mechanical damages and for making the cables heavy enough to be fixed at the sea floor.
4. Design of a Seabed Power Array System

There are several drivers for a buoy solution:

- A buoy has good accessibility to the electrical system and visual checks, maintenance, repair, and adjustments are easily performed.
- Full functionality is feasible, with various auxiliary systems, battery backup, and monitoring with good uptime within reasonable cost. It is also possible to execute a safety lock-out procedure of the breakers and disconnectors in the switchgear.
- All main equipment is readily available on the market from a variety of suppliers.

A buoy also has several disadvantages, such as:

- Cable fatigue due to buoy movements.
- The visual impact.
- Cost for the mooring system.
- Cost for buoy and operation, service and maintenance of buoy.

A future solution that is based on components on the seabed would be better from some aspects, as not being visible and not exposing the power cables for fatigue forces; however, the design philosophy needs to be modified; it should be designed with minimum complexity as it will be difficult and expensive to access for planned and unplanned service and maintenance.

The second alternative for a power system array is a system based on two main components, a simple seabed transformer for each kite, and a seabed hub, with a simple switchgear and built-in protection system.

Because of time and resource constraints, this alternative is not investigated in the same level of detail as the base case. Some parts are assumed to be similar to the base case and thus not necessary to address. In other cases, some remaining concerns or unsolved problems are listed and left to be answered in the future.

4.1 Electrical Protection System

The principle of the relay protection setup is the same as in the base case.

The design of the power supply for the protection relay system in the seabed switchgear and in the transformer enclosure need to be further investigated but is not in the scope of this report.

The protection system for the power cable to and from the seabed transformer may be excluded as the LV power cables from the kite are protected by the protection devices in the Powerkite. The MV power cable from the transformer to the seabed switchgears are protected by the switchgear devices. It may be possible to exclude all cable protection devices in the transformer enclosure. The remaining protection devices in the transformer enclosure are exclusively for the transformer as overheating and overcurrent protection; as a result, a monitor system is required for the transformer to facilitate disconnection of the power cables from the transformer in the feeding and collecting systems. Such a monitoring system for the transformer is not yet developed.

4.2 Array Modelling and Calculations

For the seabed case, there was no detailed electrical model developed.
The cable design was based on simplified calculations for load currents, voltage drop, earth fault and short circuit currents. The maximum allowed current is never exceeded by the calculated currents. Voltage drop was calculated to be less than 2%, confirming that the conductors cross-sectional area are large enough.
5. Array Description for 80 MW Seabed Case Array System

In this chapter the design of the 80 MW seabed solution is described.

5.1 Array Size and Structure

The seabed design is based on a 2 MW sub-array of 4 0.5 MW kites with seabed transformers connected to one seabed switchgear unit as in Figure 31. 12 of these sub arrays are connected using seabed switchgears forming a 24 MW unit that is connected to shore via an export cable. Three 24 MW units with three export cables form the full array as shown in Figure 32.

For the Seabed 80 MW case the array is thus defined as 144 kites, 48 seabed switchgears, and 3 export cables. The rated power is effectively 72 MW but referred to as 80 MW for simplicity. The structure and size of the array is dependent on the requirement to be able to recover the individual seabed switchgear units which results in relatively long cables. A suggested topology can be seen in Figure 32. A SLD for an 80 MW array follows in Figure 33.
Sub-hub cables are designed for actual load, i.e. cable cross sections for the inter-array cables increase, as the power is accumulated along the chain.
Figure 33. Single line diagram for 80 MW system

### 5.1.1 Transmission efficiency

No detailed calculation model was setup for the Seabed solution. Instead of performing detailed load flow calculations, a transmission efficiency was calculated in a spreadsheet using a model based on using load and impedance in cables at each cable for output power from 100kW to 500kW, 500 V and 3000 V. The cases are compared in Table 6 below. The results conclude that there is no big difference in efficiency between the two 500 V cases but a significant improvement using 3000 V as generator voltage.

<table>
<thead>
<tr>
<th>Kite Voltage</th>
<th>Efficiency 500 V</th>
<th>Efficiency 3000 V</th>
<th>Energy Weight (AEY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power [kW]</td>
<td>Base Case</td>
<td>Seabed</td>
<td>Base Case</td>
</tr>
<tr>
<td>100</td>
<td>97,1</td>
<td>97,0</td>
<td>98,3</td>
</tr>
<tr>
<td>200</td>
<td>95,4</td>
<td>95,7</td>
<td>97,6</td>
</tr>
<tr>
<td>300</td>
<td>93,5</td>
<td>94,1</td>
<td>96,8</td>
</tr>
<tr>
<td>400</td>
<td>91,5</td>
<td>92,4</td>
<td>95,8</td>
</tr>
<tr>
<td>500</td>
<td>89,6</td>
<td>90,8</td>
<td>94,9</td>
</tr>
<tr>
<td>Energy Weighted average [%]</td>
<td>93</td>
<td>94</td>
<td>96</td>
</tr>
</tbody>
</table>
Table 6: Transmission efficiency comparison of base case and seabed case

## 5.2 80 MW Seabed Solution Components

### 5.2.1 Kite Generators

Variable speed PM generator with back-to-back converters AC/DC – DC/AC in each kite.

Kite output voltage is 500 V, 500 kW rated power

Identified key requirements related to kite, and array, design:

- Voltage at kite output to be controlled within 90 – 110%.
- Kite must withstand grid disconnection at 100% load
- The kite as individual generator system must be able to start and stop production smoothly in synchronization with the grid, without large step voltage changes. The setup of the kites in the base case, as variable speed generators with back-to-back converter enables this. Fixed speed generators would need special synchronization devices.

### 5.2.2 Umbilical cable

The umbilical cable in this case has only one part, the tether part with four individual three-phase power cables and FO cable integrated in the protective tether fairing. Conductor cross section is a compromise between electrical losses and available space in tether. It contains 4/50mm² cables. A visualization of the cable is included in Figure 34. Note that the tether profiles are preliminary design examples and not indicative of what would installed.

In the seabed case, after the bottom joint, the umbilical is connected to the seabed transformer directly. This has not been investigated in detail, but wet mate connections to the seabed transformer is one possible option that has been used here.

The tether is assumed to be serviced every 5 years, which is 5 times during the 25-year design life of the system. To avoid lifting the seabed transformer when the tether is replaced, the umbilical is equipped with wet mate connectors so that the umbilical can be installed with the seabed transformer on the seafloor.
Seabed Transformer

For the high-power kite generators, low output voltage results in high currents, and consequently high losses if the cables are long and limited in cross section area. In this case the cross-section area and cable size are limited due to mechanical forces on the tether.

A possible solution is to place a step-up transformer close to each kite. A transformer is a relatively simple device, so the design philosophy would be to design unit that is fit for design life (25 years) but retrievable for replacement and repair if a fault should occur.

Figure 35 is a schematic description of a seabed transformer design. The transformer is installed at a depth of 100-200 m. Different connection configurations are possible, in Figure 35 the transformer has one 3-phase dry mate connector at the HV side and four 3-phase dry mate connectors at the LV side.

The example showed in Figure 35 is a 630kVA 0.5/24kV dry-type transformer housed in a cylindric enclosure designed to withstand the water pressure at 100 meters depth, which is suitable for a 500 kW Kite.

The transformer weight is approximately 2000 kg in dry weight. Together with the housing and connectors the weight is about 6000 kg in dry weight. The size of the housing in this example is: Length (X =) 2500 m and diameter (Y =) 3000 m.
A concrete block or ballast of some kind is required to install the transformer at the seafloor. The Buoyancy is estimated to about 10000 kg for this size of transformer, giving a necessary total weight of approximately 26-30 tons.

Ideally, the subsea transformer should be liftable and transportable using the same vessel as used for the kite operations; however, a 50m DP vessel may be required to handle these seabed transformers.

The Subsea transformer is placed at the seafloor nearby or at the bottom joint as shown in Figure 36.

### 5.2.4 Seabed Switchgear

This solution is built on subsea switchgears with 3-5 legs with built in relay protection, breaker control, and equipped with dry mate connectors for the cables. It is based on a system which is commercially available.

The switchgear which is used in this case is equipped with load breakers, disconnectors, earthing switches, and protection devices. It is possible to maneuver the breakers, disconnectors, and earthing switches remotely and monitor the status of the switchgear and the position of the breakers and other components. The switchgear is installed in a hermetically closed enclosure which is watertight at 100 meters depth.

The design philosophy is the same as for the seabed transformer, with a requirement for a 25-year service life with no periodic service and maintenance requirement. The device should be retrievable for replacement and on shore repair if a fault should occur.
Connectors are dry mates for 24 kV. If the device needs replacement, the unit is brought to the surface, and a replacement unit will be installed. Adequate cable topology is necessary to enable recovery without cable damage or entanglement.

![Figure 37. ETA Smart Hub](image)

Connectors are dry mates rated to 800 amps @ 36 kV. The SmartHub is currently limited to 630 amps @ 24 kV.

The auxiliary power is normally provided from the shore via an LV core contained within the export cable. Since the distance to shore is no less than 8-15 km, it is not a possible solution, other solutions are investigated but are not presented in this report.

Assuming all device cables have already been laid, deployment of the seabed hub with cables attached is dependent on water depth; however, it should be possible to complete within 24 hours. There are various installation strategies available, and they will have varying time advantages and disadvantages.

One big advantage is that installation and recovery can be performed with a 28 m Multicat boat, which indicates relatively low operational costs.

### 5.2.5 Inter-Array Cables, Sub-Hubs, Hubs, and Export Cable

For the seabed solution cables were dimensioned according to simplified calculations as described under 4.2.

The resulting cable specification are described in Table 7 below.

<table>
<thead>
<tr>
<th>PTO</th>
<th>Cable No.</th>
<th>From-To</th>
<th>Length [m]</th>
<th>No. Cables</th>
<th>Size [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTO.11</td>
<td>W 101</td>
<td>Onshore-S100</td>
<td>8000</td>
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Cable costs are generally difficult to estimate, so multiple sources were used.

One source was to estimate cable cost for inter-array and export cables from EBR Kostnadskatalog, which is a tool used by Swedish DNO’s to estimate project costs. In the EBR catalogue, costs are listed for different applications. Code G149 - “PEX, 24 kV Sea-armored cable with application for sea or large lakes” was used. Costs were split into material costs and installation costs, where installation costs were calculated as the total costs minus the material costs. Costs for cable cross sections not listed were estimated using interpolation. These costs were found to be generally quite low, presumably since conditions in Scandinavia requires less advanced cables than e.g. the Irish Sea.

As a second source cable prices were estimated by compiling information from suppliers and other contacts. These prices are higher mostly due to a more robust cable design proposed, with double steel armoring.
6. Comparison of Base Case with Seabed Solution

The initial design of the umbilical cable between the PTO and the TMS and the use of a low voltage system, (500 V from the PTO to the TMS) resulted in high electrical losses. Alternative designs of the umbilical cable in conjunction with a higher voltage level were defined as a way to reduce these losses to acceptable levels.

Fluctuations in the output voltage level need to be balanced to stay within required limits. One possible mitigation is grouping six kites together as one production group with 60 degrees shifting between each power kite.

The power factor and voltage variations at the point of connection to the grid were not always within the specified limitations. The base case solutions therefore include a reactive power compensation unit, active control of the power factor of individual kites and the use of an online tap changer at the power transformers in the on-shore substation.

A number of relevant standards and requirements for the design and installation of an offshore power generating system have been investigated, identified and used in the design work.

A base case design for the tidal kite array was proposed, consisting of the 6 kites connected to the Tidal Marine Substation (TMS). This sub-array was extended to build up a 80MW array.

The array infrastructure design included standard components chosen for their robustness and with focus on a short time to implementation and lower cost. For the TMS buoy, the mooring system is the costliest part, the electrical components are comparatively cheap.

The TMS buoy design includes: hull structure, layout of electrical equipment, cable handling and mooring solution. The TMS hull contains LV and HV transformers and switchgears allowing connection of up to 10 TMS in a daisy chain arrangement. The movements of the kites and the TMS buoy during operation proved to be a design challenge for the cable connecting systems, as cables of high endurance and robustness combined with high flexibility are required.

An alternative, seabed array design was also developed. The seabed design is based on a sub-array of four kites with seabed transformers connected to one seabed switchgear unit (SmartHub). This sub-array was extended to build up an 80MW array.

When comparing the seabed and the buoy solution, it is clear that it is not possible to achieve the same level of accessibility to the electrical system, and its devices, in the seabed as in the buoy. If a major fault occurs which requires visual check, repair, adjustment, or similar, it is relatively easy to gain access to the electrical parts by entering the switchgear room inside the buoy. If this happens in the seabed switchgear, it needs to be lifted up to the sea surface and some of the cables must be disconnected.

To realize the 25-year design life of the seabed switchgear and minimize its requirements on maintenance, careful consideration needs to be given to what to include in it terms of auxiliary systems like battery backup, communication, monitoring, and other systems.

Some of the devices from the buoy system may be removed in the seabed solution, but others are vital to operation and must be included, e.g. the battery backup system and a monitoring system. The suggested LV auxiliary system, with a LV supply from the onshore connection point, is limited by the large voltage drop of long cables. In the reference case, with cable lengths exceeding 10 km, a power supply system is most probably needed inside the seabed switchgear enclosure. A battery backup system would make it possible to monitor all systems in the enclosure and operate the breakers regardless if the MV array system is energized or not.

For the seabed solution there is a lack of possibilities to execute a manual physical safety lock-out procedure of the breakers and disconnectors located inside the seabed switchgear. If the requirements in IEC 50110 shall be
fulfilled (during, for example, a maintenance operation inside a subsea hub) it means that the nearest onshore disconnection point is to be used for the lock-out procedure and this means that the portion of an array that is connected to that particular export cable is disconnected and taken out of service during the maintenance operation. IEC 50110 is written for humans operating in air. There might be ways to engineer kites and machinery that performs the operation of disconnecting and connecting a kite to their subsea system truly remotely in such a way that IEC 50110 may not be the most appropriate standard. The applicability and relevance of IEC 50110 for subsea kites and associated subsea hubs is a subject that requires further study.

The TMS buoy requires a mooring system that is complex and requires maintenance.

The seabed concept has no visible part above the surface which is a very important advantage over a buoy solution.

Umbilical losses in the systems depend primarily on kite output voltage. Generally, the higher voltage, the lower the umbilical losses. For 500V kite generators, the losses are high at higher power. A large part of these losses is created in the tether cables. The size of the tether cables is limited in order not to create a too large tether that slows the kite down. In the seabed case, these losses are limited by placing a transformer close to the kite foundation, therefore only the tether cables are subject to substantial losses for lower voltages. For 3 kV kites, umbilical losses are small and acceptable for both buoy and seabed concepts.

Array losses, i.e. the losses after the first transformer, are small and the differences between the base case and seabed concepts are minimal since the voltages are sufficiently high (24/36 kV). For all cables after the tether, the cable size is determined by the maximum current, and consequently the losses are largely determined by cable length and the inter-array voltage. This results in similar efficiencies for the different alternatives, with only minor variations.

The impact of kite voltage for the base case solution is as follows:

- At 500 kW, 500 V will work but the voltage is too low for an optimal solution. It requires a special umbilical with large cable areas. It also calls for tightly-packed kites since a maximum distance between kite and TMS buoy restricts the layout of kites on the seabed.
- Increasing the voltage to 690 V provides a working solution for 500 kW kites, however for higher-powered kites the cable will again become limiting.
- With 2.2 kV or 3 kV kites, the currents for a given power are much smaller, so the available space in the tether is enough to fit in cables that give small losses even at high powers.

Umbilical cable cross section and maximum length – the buoy concept requires a 3 kV output voltage to enable freedom in the location of the kites on the seabed. The seabed concept gives freedom in the location of the kites on the seabed for all voltage levels. The low-voltage buoy concepts require the kites to be located close to the TMS, max 500 m umbilical length.

Cable fatigue is one of the larger technical challenges in general, but especially for the buoy concept. Achieving a 25-year design life in the conditions of a moving buoy with cables in a moving current is not trivial. For the cables that lie on the seafloor, stabilizing the cables may or may not be an issue, depending on the constitution of the seabed and the direction and velocity of the tidal current at the seabed. The seabed concept is inherently more sensitive to cable stability issues. If the cables have to be fixed to the seabed using blocks or rock cages (for example), the replacement and repair operations of seabed components will be more complicated.

Mean Time Between Failure (MTBF) for Subsea components – the base case was developed using standard off-the-shelf components that are well tested and readily available. The components are available in a buoy that is rather easily accessible. The seabed concept is built on a wholly different principle. The philosophy is to use as robust and simple components as possible, for a design life of 25 years. (Switchgears and protection systems
include moving parts for which makes it difficult to guarantee a service life of 25 years without any planned maintenance). The cost for investment and maintenance is low compared to the base case if the 25-year design-life assumption is true, but the technical risk is higher since the technology is not as mature as that of a TMS buoy.

Technology maturity/availability – subsea transformers are available for offshore oil and gas applications since the end of the last century. Adapting these for marine renewable energy applications requires engineering efforts resulting in cost reductions.

Marine interaction – a TMS buoy is located on the sea surface and vessels could run into and damage it or its mooring system.
7. Conclusions

For the location of Holyhead Deep, this report describes two conceptual designs of complete 80-MW offshore array systems including substations, cables, and an on-shore grid connection. Initially, a base case array design was developed based on Tidal Marine Substation (TMS) buoys. Later, an alternative subsea array design was developed based on sub-hubs located on the seafloor. The report gives an overview of the array components and discusses briefly operational consideration and constraints. A sister report focuses on installation, service and maintenance strategies [1].

In the design work on the base case solution, relevant requirements and recommendations were identified and applied from grid code [2] as well as from electrotechnical standards [3]. Array operational modes and a Supervisory Control and Data Acquisition (SCADA) system are briefly outlined. Protection requirements for onshore and offshore systems are described.

A theme that runs throughout the report is that of kite (generator) voltage. The kite voltage determines generator power, tether cable diameter, transmission losses, and possible distance from kite to transformer (or hub).

As the kite flies in its 8-shaped trajectory, the speed of the kite varies, and this results in variations in output power. These variations can be mitigated on array level by controlling kites to fly offset to one another in their trajectories and on kite level by generator control and kite design.

Most of the engineering effort described in the report was based on the TMS buoy solution. The subsea hub solution was developed later and is described in less detail. Both solutions have their strengths and weaknesses. For the TMS buoy solution, the components required are more technically mature and available on the market. On the other hand, the subsea hub solution offers the compelling prospect of no visual impact and less requirements on maintenance, given that the technologies it requires mature. In particular, the subsea solution requires subsea switchgear and subsea transformers at reasonable cost and with long service intervals.

The report ends with a detailed comparison between the two solutions. Reliability and maintainability are major factors that determine the cost-effectiveness of each solution and should be kept in mind as further array concept solutions are explored and developed in the future.
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References