Ref. Ares(2019)669394 - 05/02/2019

Power Take-Off System for a Subsea Tidal Kite

D5.2
Commercial Service and Maintenance Strategy Report

	Deliverable number	Lead Beneficiary	Type	Dissemination level
	D5.2	Minesto	R	Public

	Editor	Kat Wilson
	Authors	Kat Wilson, Per Salomonsson, Patrik Pettersson

Document history

Version	Author	Beneficiary	Date	Comment
1.0	Kat Wilson	Minesto	2019-01-31	Final version

Content

Internal Approval

Coordinator signature

Per Salomonsson

Digitalt signerad av Per Salomonsson
DN: cn=Per Salomonsson, c=SE, o=Midroc, email=per.salomonsson@midroc.se
Datum: 2019.02.05 19:02:03 +01'00'

Name	Company	Date

Reviewer signature

MINESTO	2019-02-01

Name	Company	Date

BERNT ERIK WESTBERG

Abbreviations/Acronyms

COE	Cost of Energy
CAPEX	Capital Expenditures
DG	Deep Green
DP2	Dynamic Positioning (level 2)
DPM	Distributed Power Module
HPP	Hydraulic Power Pack
kW	Kilo Watt
LARS	Launch and Recovery System
LBE	Laborelec
LCOE	Levelized Cost of Energy
MIN	Minesto
MTBF	Mean Time Between Failure
MW	Mega Watt
OPEX	Operational Expenditure
PTO	Power Take Off
QUB	Queen's University Belfast
REH	Rudder and Elevator Housing
ROC	MIDROC
ROV	Remote Operated Vehicle
TOM	Turbine Operating Module
TMS	Tidal Marine Substations
UPS	Uninterruptable Power Supply

Executive summary

A goal of the PowerKite project is to develop a conceptual design of the complete offshore cable array system including an onshore grid connection.

This report defines the base case for an 80 MW array of 160 operating power plants (kites) each rated at 500 kW connected to 27 electrical substations installed at the Holyhead Deep operational site in Wales. It discusses the implementation and organization of the array as well as a maintenance and operational strategy.

As it discusses the overall maintenance strategy and implementation, the report defines each of the inputs and clarifies any assumptions made. The report then identifies areas of improvement to the overall strategy and implementation and explores them.

As the report explores the power plant maintenance strategy, it defines the expectations for the planned and unplanned work, the offshore and onshore handling strategies and activities, the workshop requirements, as well as a spare parts strategy. The discussion on power plant maintenance strategy concludes with identifying opportunities for improvement and explores how these could be designed and implemented.

The report then assesses the array components maintenance strategy. The discussion on the maintenance strategy identifies future possibilities for optimization and improvement.

The majority of the work is based on the DG500 prototype design. This is adequate for a base case study as defined in the scope of this report but does not reflect what would be realized in an actual array roll out. The Deep Green technology undergoes a continuous development process, including performance enhancements, reductions in system complexity, handling and installation improvements and a shift towards using fewer components. The technology benefits from issues identified and addressed in PowerKite, such as operational constraints and practical considerations highlighted in this report, but also from development of hardware and key components such as turbine and tether. In addition, the offshore and operational campaigns with DG500 in 2018 have been beneficial for the organization in identifying strengths and weaknesses in the design.

As the report concludes it introduces, evaluates and compares other array cases regarding their installation, service, maintenance strategy, and cost. With the assumptions made in this study the levelized cost of energy for arrays of more powerful kites is significantly lower compared to the 500 KW base case.

Background

This report is the deliverable from PowerKite project Task 5.2. The project application describes this task as the development of strategy of the installation, service, and maintenance procedures for the commercial array power system.

The work will be collaborative between ROC, QUB, LBE, and MIN project partners. The contributions are listed as follows:

- ROC lead this work package and were supported by consortium members in the various parts of the work package.
- QUB provided the weather modelling
- LBE performed electrical modelling and simulations and reviewed the commercial array power system design
- MIN has provided the installation, service, and maintenance procedures and supported the electrical design

Scope

This report outlines a commercial installation, service and maintenance strategy, based on the PowerKite PTO system installed in a current DG500 power plant design and the suggested base case array of 80 MW developed by PowerKite in report D5.1. The overall array is first discussed, then the power plant and array components are also isolated and discussed. This base case is then compared to other array cases in terms of cost and operation and maintenance strategy. This report will include, but is not limited to, the following topics:

- Definitions and assumptions
- Array, power plant, and array components maintenance concepts and strategies
- Definition of planned and unplanned work expected
- Offshore, onshore, and workshop handling capabilities and strategies
- Operational strategies for retrieving, launching, loading, offloading, servicing, and maintaining power plant
- Spare part and inventory strategy
- Workshop setup and operational strategy
- Comparison of array cases to array base case
- Cost and operational comparison for installation, service, and maintenance of array
- Identified opportunities for improvement to strategy for array, powerplant, and array components

1. Definitions

Definitions are provided for significant terms and components for clarity of report content.

1.1 Kite

The power plant is also referred to as the kite. The base case kite is defined as the DG500 prototype (500 kW capacity).

1.2 Array

Report [2] contains in-depth analysis of the different available array power outputs to achieve what is reasonably nearest to 80 MW intended development at the Holyhead deep site in Wales. A Summary of this information can also be found in Table 8 in this report. It can be noted that in Report [2] a full array is considered 78 MW for the 500kW kites, but this report uses 80 MW for a full array.

For this report, a theoretical situation is analysed where 80 MW is achieved. 80 MW would be the total capacity for the Holyhead Deep site, but the capacity could be larger if more powerful kites are installed instead, and/or in combination with shorter tethers which could also improve the packing density.

It is not necessarily realistic to choose to implement a TMS system for an 80 MW array, but for the sake of completeness this system is analysed throughout this document. In order to achieve this 80 MW array case, each TMS buoy can operate 6 (six) kites in the base case system which totals to 3 MW per buoy. There will then be 26 (twenty-six) such buoys operating at 3 MW each and an optional 27th (twenty-seventh) buoy which operates at 2 MW to achieve the target 80 MW array system.

The total components for the 80 MW array:

- 160 operating kites
- 27 electrical substations
- 16 spare kites

There is an umbilical for each kite to the nearest TMS (Tidal Marine Substation), where voltage is transformed to export level (33kV) and daisy chained until the final export station acting as the export hub. Figure 1 shows the conceptual layout for one 6-kite (3 MW) cluster and one TMS (buoy). The diameter of each visualized circle in the figure is 250m, equal to 2x tether length plus kite.

No studies have been made on impacts of higher voltages on number of TMS buoys. Higher voltage would allow for longer cable runs, and consequently another pattern of buoys. Buoys would have to be slightly larger, but fewer to the count.

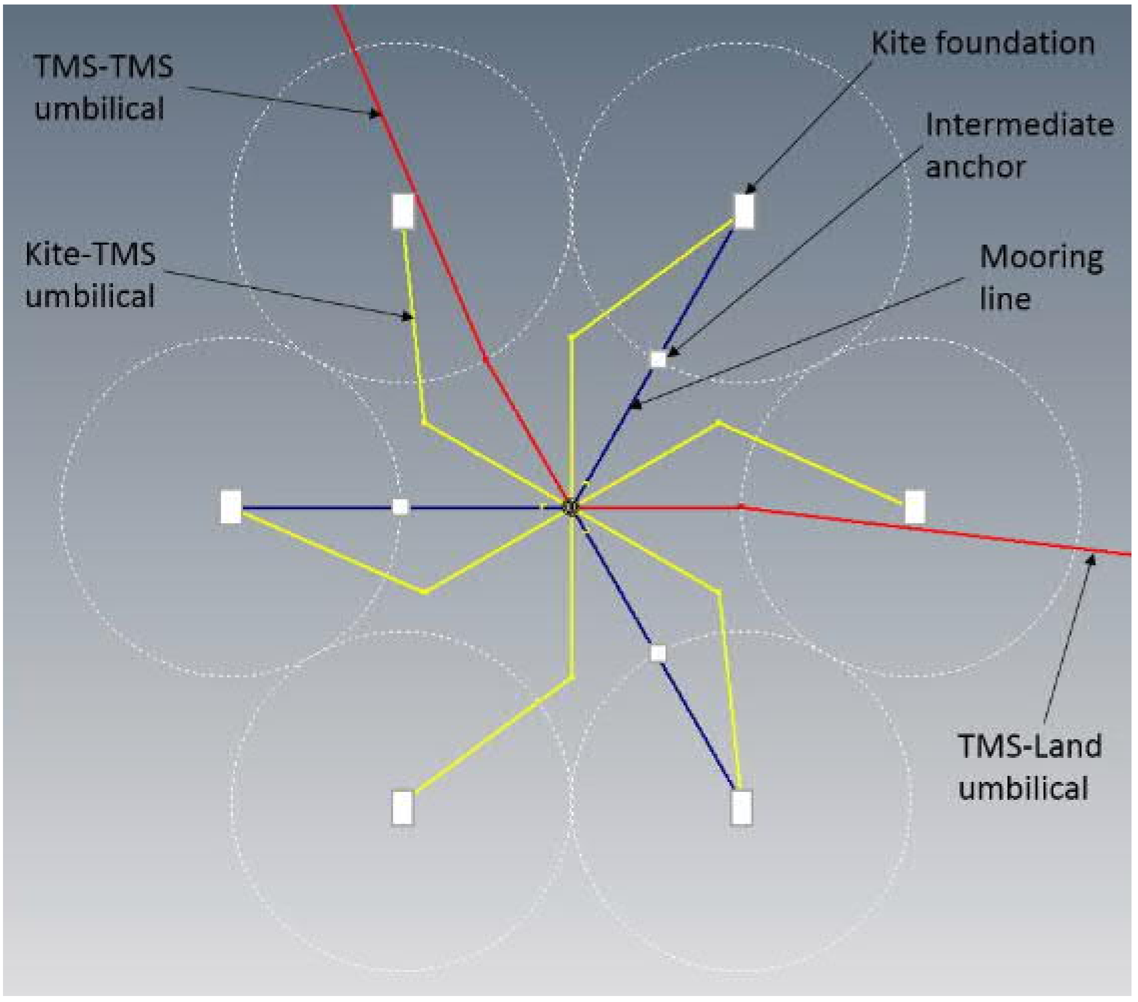

Figure 1 Kites and TMS Configuration

1.3 TMS

The TMS collects electric power input from the operational kites, processes the input, and transforms from kite output voltage to inter array voltage. The current design of a TMS buoy is an intermittently manned Buoy which contains transformer, LV/HV switchgears, Uninterruptable Power Supply (UPS), and auxiliary components such as pumps and fans, equipment for cable connections and communication equipment. The buoy is designed to be cylindrical with a 15 m height and 5 m diameter, as visualized in Figure 2: TMS Buoy definition.

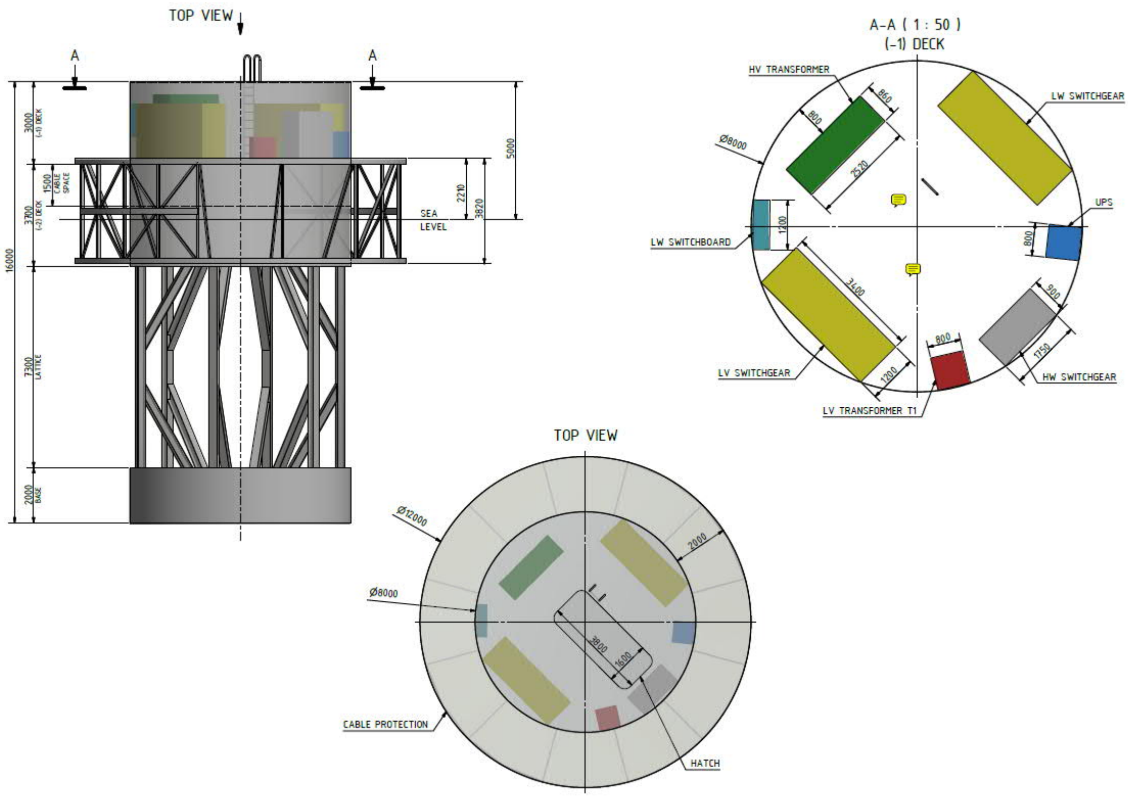

Figure 2: TMS Buoy definition

1.4 Inter-array and Export Cables

Follows is a list of array cables:

- Umbilical cables (from power plant to TMS)
- Tether power and optic cables
- Export cables
- Inter-array cables

The cables are bundled and visualized in Figure 3: Inter-Array Cable Visualization.

Figure 3: Inter-Array Cable Visualization

1.5 Operational Site and Conditions

The operational site is located at Holyhead Deep. It is visualized below in Table 4. The weather conditions are discussed in Section 2.1.7.

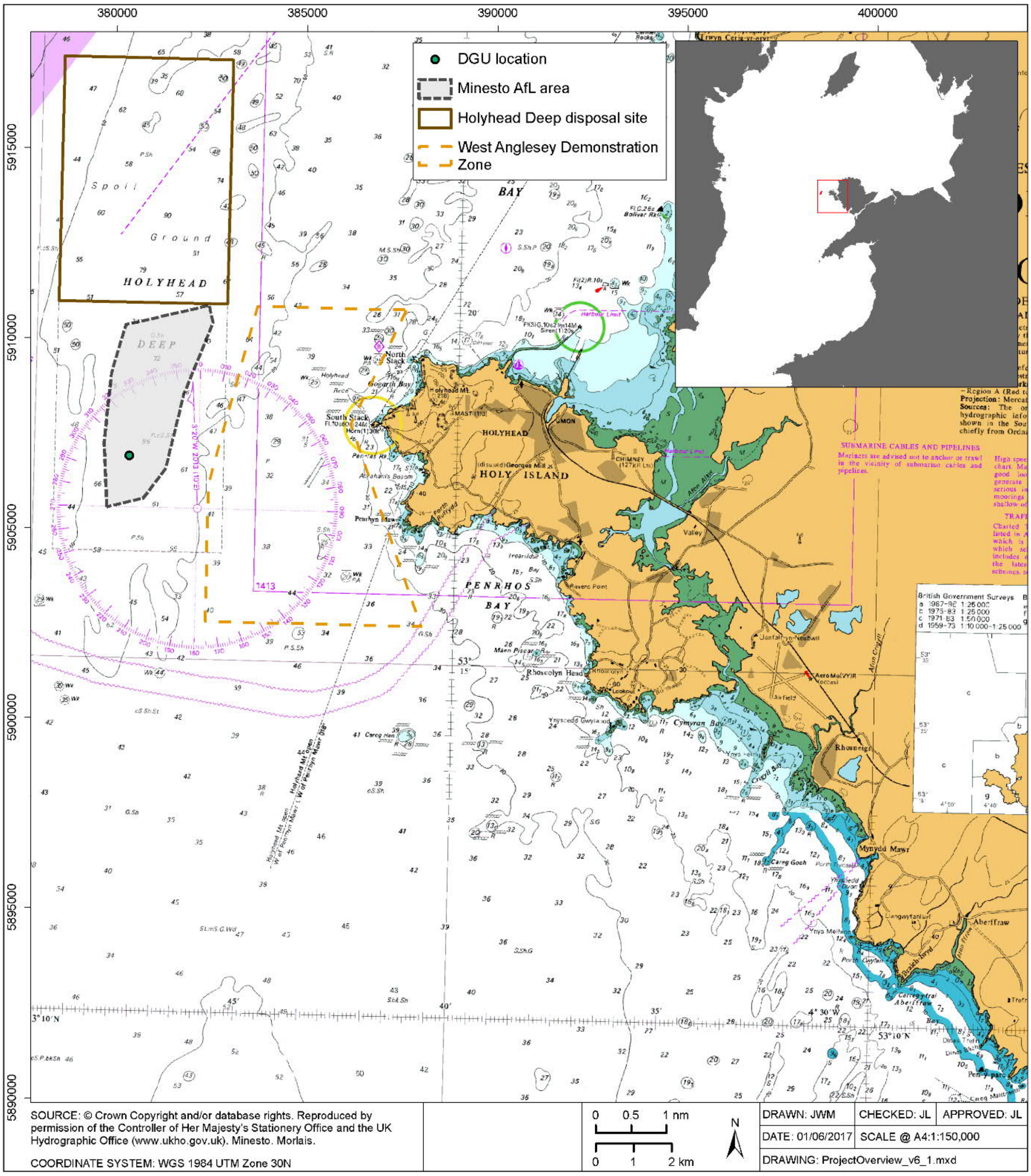

Figure 4: Holyhead Deep Operational Site

2. Maintenance Concept and Strategy

This section contains the in-depth maintenance strategy for the base case array at the Holyhead Deep site. The higher-level comparison and analysis between the alternative array cases is included in section 5 Array Evaluation and Comparison.

2.1 Definition and Assumptions

2.1.1 Inter-Array Cables, Export Cables, and Electrical Substations

Routine inspection of cables is assumed to take place every 5 (five) years. This is an activity separate from the regular maintenance, as approximately 1 month of effort every 5 years easily can be addressed with a subcontracting mechanism. The same applies for non-planned work required on the cable systems, estimated to happen once every 15 years. Although such interruptions may cause downtime on the overall system, these events will be covered with subcontracting mechanisms.

The electrical substations will be designed for the lifetime of the facility and will be scheduled for an annual inspection programme. This programme does not require the electrical substations to be shut down. Every five years a major intervention is planned for these buoys, requiring electrical systems to be shut down to be able to execute the work safely. Such operations are performed using subcontracted vessels, with Minesto personnel supported by supplier representatives. This work should be coordinated with scheduled work on kites and substations.

2.1.2 Kites

Each kite is subject to one planned and one un-planned inspection and maintenance activity per year. When a kite is being inspected or maintained, it is disconnected from the tether and replaced with another kite.

It is assumed that it will take 1 (one) hour to connect/disconnect a kite from the tether, including time to recover and launch the tether buoy, and confirmation that kite is successfully connected to the substation.

It is also assumed that the kite has been instructed to return to surface and is available for recovery when vessel arrives.

The kite must be electrically isolated onboard the substations.

2.1.3 Vessels

It is likely that a vessel would be purchased and operated by the array owner for a large array of kites. The vessel assumptions are based off a 33m Multi-Cat DP2 vessel.

A typical distance covered for one round trip from Holyhead to one given kite location is 12 nm, with each way being 6 nm. The vessel will then need approximately 1 hour from location to dock allowing slower speeds in harbour areas and period for docking.

An additional crew transfer boat is required to shift personnel between the substation and the vessel. This operation adds 30 minutes to each kite operation.

This report assumes the vessel is always available. This will not be the case, as any vessel will be subject to various yard visits for repairs, reclassification, and other activities. Report assumes another identical vessel is available in these periods.

The operation of loading and offloading kites from the vessel is assumed to take one hour per operation. Offloading a kite and immediately loading another kite is assumed to take 2 hours. The vessel can bunker fuel, consumables, and other supplies during these loading and offloading operations.

2.1.4 Onshore Workshop

The quayside draft is assumed to always be sufficient for docking, loading, and offloading procedures. In the base case for a large array, it is assumed that a docking space would be dredged or otherwise modified to allow for continuous operation.

The workshop must have the capacity to receive and dispatch kites on a frequent basis and must have capacity to service 16 kites.

This report assumes the workshop can deliver a kite to the quayside whenever the vessel arrives, and no transport time between the workshop and vessel is included in the planning.

2.1.5 Kite Tether Replacement

The tether is assumed to require replacement every five years. This is a one-day operation, and it can be performed when subject kite is recovered. This results in 160/5 = 32 tether replacements annually. This work can be scheduled around other maintenance work and will take place in a suitable weather campaign in the summer.

The operation would need to include an additional day to bring the tether to and from the shore.

2.1.6 Total Duration for Replacing One Kite

One duration for replacing one kite is shown below in Table 1 , beginning with loading a kite and ending with offloading a kite. There is an assumption that the DP Vessel can only manage one kite at a time.

Activity	Duration (minutes)
Load kite	60
Drive to site	60
Crew transfer to buoy	15
Retrieve tether	30
Connect and launch kite	40
Drive to next kite	5
Recover and disconnect kite	60
Crew transfer from buoy	30
Return to base	60
Offload kite	60
Total duration (minutes)	420
Total duration (hours)	7

Table 1 Duration of Replacing One Kite

An example of a one-day operational period of loading and offloading a kite starting without a kite on the ship is shown in Table 2 Duration of One day Vessel Operation, No Kite at Start.

Start	Activity	Duration (Minutes)	Note
06:00	Drive to site	60	Steam out with no kite
07:00	Crew transfer to buoy	30	
07:30	Recover and disconnect kite	60	415 minutes between connections, lost production
08:30	Crew transfer from buoy	30	
09:00	Return to base	60	
10:00	Offload kite	60	
11:00	Load new kite	60	
12:00	Drive to site	60	
13:00	Crew transfer to buoy	30	
13:30	Retrieve tether	15	
13:45	Connect and launch kite	40	
14:25	Drive to next kite	5	
14:30	Recover and disconnect kite	60	No kite on this slot from 14:30
15:30	Crew transfer from buoy	30	
16:30	Return to base	60	
17:30	Offload kite	60	
18:30	Load kite	60	
19:30	Boat loaded, wait	0	
Total duration (minutes)		780	
Total duration (hours)		13	

Table 2 Duration of One day Vessel Operation, No Kite at Start

The following table contains the duration of a one-day operational period of loading and offloading a kite starting with a kite on the ship, shown in Table 3 Duration of One Day Vessel Operation, Kite at Start. This day could hypothetically follow the day shown in the previous table, so these tables can be combined to form a two-day operation; Alternatively, Table 3 schedule can be repeated over several days.

Start	Activity	Duration	Note
06:00	Drive to site	60	Kite loaded onto ship
07:00	Crew transfer to buoy	30	
07:30	Retrieve tether	15	
07:45	Connect and launch kite	40	Kite operational around 08:30 (18 hours)
08:25	Drive to next kite	5	
08:30	Recover and disconnect kite	60	415 minutes between connections, lost production (about 7 hours)
09:00	Crew transfer from buoy	30	
09:30	Return to base	60	
10:30	Offload kite	60	
11:30	Load new kite	60	
12:30	Drive to site	60	

13:30	Crew transfer to buoy	30	
14:00	Retrieve tether	15	
14:15	Connect and launch kite	40	
14:55	Drive to next kite	5	
15:00	Recover and disconnect kite	60	
16:00	Crew transfer from buoy	30	
16:30	Return to base	60	
17:30	Offload kite	60	
18:30	Load new kite	60	
19:30	Boat loaded, wait	0	
Total duration (minutes)		840	
Total duration hours		14	

Table 3 Duration of One Day Vessel Operation, Kite at Start

There is an 18-hour gap between the time that the kite is retrieved, and a new kite is connected the following day. There are also approximately 7 hours of production loss due to the amount of time required for a round trip. This is a total of 24 hours loss of availability of one kite when planned maintenance is undertaken.

This loss will be reduced to 2 hours if the vessel can handle two kites simultaneously.

2.1.7 Weather Availability for Maintenance and Service Work

The operations are restricted by weather conditions. An in-depth study on the weather and conditions at Holyhead has been performed and is available in Report [1]. Additional weather conditions discussed in this report include, but is not limited to, wave, current, wind, and water level data as well as daylight hours and other site conditions.

Wave height is the critical consideration when reviewing site weather conditions with respect to operations. A summary of the annual anticipated wave heights per month is included in Figure 5 Holyhead Deep Annual Down Time Due to Wave Height. As can be observed, the months November through January have limited availability and are therefore not included in the planned maintenance work schedule.

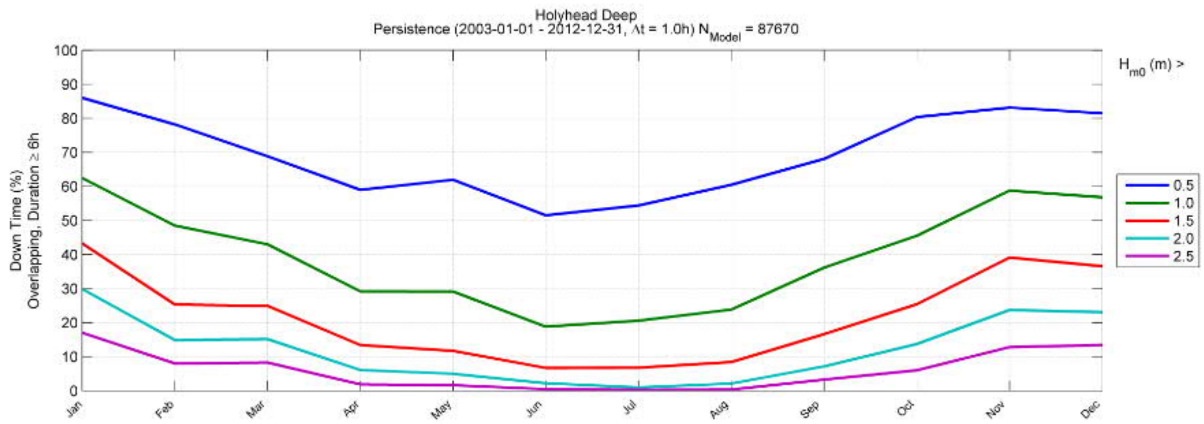

Figure 5 Holyhead Deep Annual Down Time Due to Wave Height

The favourable operation period is 8 months (245 days) inclusive of March through October. Presuming a 20% (49 day) loss of availability due to weather, there remains 195 days for planned maintenance. The unplanned activities are distributed evenly over the year, which returns 160/12 = 13.3 kites/month. This consumes 106 days over the 8-month planned operational period; therefore, planned maintenance of all 160 kites must be executed over 90 days.

For the purpose of this report, it is therefore assumed that 2 (two) kites are being brought in for service daily. This is either a planned activity, or one of the unplanned replacements required. An example of this operation is included in Table 3 Duration of One Day Vessel Operation, Kite at Start. This operation can only work if the tether can be disconnected overnight. There will be a production loss during the overnight period.

Launching and recovering 2 kites consumes 14 hours of vessel operation.

Once a kite is brought in for unplanned replacement, it would also have the planned maintenance program performed; however, since the unplanned maintenance may not align with the planned maintenance program this option is disregarded in this report and the base case of two replacements per year is used.

2.1.8 Kite Replacement Plan

Table 4 Conceptual Kite Replacement Table, shows a plan for replacing kites within the array. Kite K1 must be available for operation on day 9. Day 1 and Day 9 are both partially unavailable for work due to operational retrieval and launch, which leaves six full days and two partial days to complete all work on this kite. A given kite must be able to be fully restored in seven calendar days, returning a one-week turn around requirement on the workshop.

The workshop must be capable of working on 16 kites at any point in time, as well as the handling of the kites, without disturbing the ongoing activities of the kites in the workshop.

Day	Kite	Replacement Kite
1	K1	S1
1	K2	S2
2	K3	S3
2	K4	S4
3	K5	S5
3	K6	S6
4	K7	S7
4	K8	S8
5	K9	S9
5	K10	S10
6	K11	S11
6	K12	S12
7	K13	S13
7	K14	S14
8	K15	S15
8	K16	S16
9	K17	K1
9	K18	K2
CONTINUE IN PATTERN		

Table 4 Conceptual Kite Replacement Table

The operation steps highlighted in Table 4 Conceptual Kite Replacement Table are expanded upon as follows:
Day 1:

- Vessel drives to site, recovers kite K1 from tether and returns to shore
- Vessel offloads kite K1 on quayside, loads kite S1 (spare #1), and returns to site
- Maintenance work initiated on kite K1
- Vessel connects kite S1 to tether
- Vessel continues to kite K2, and recovers it and returns to shore
- Vessel returns to shore and offloads kite K2, loads kite S2 (spare #2), and returns to site
- Maintenance work initiated on kite K2
- Vessel connects kite S2 to tether

Day 2 – 8:

- Maintenance work performed on recovered kites in workshop
- Vessel continues to operate between the workshop and the site, swapping kites as per Table 4.

→ Day 9:

- Vessel continues to kite K17, recovers it, and returns to shore
- Vessel returns to shore and offloads kite K17, loads kite K1 (served and ready for operations), and returns to site
- Maintenance work initiated on kite K17
- Vessel connects kite K1 to tether

2.1.9 Workshop Scheduling and Planning

If planned maintenance requires five days per kite, a typical bay plan for the workshop is shown in Table 5. In theory, all activities in workshop could take place in workdays only, but the logistics to and from the site will not work then.

		WORKSHOP BAYS															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
DAY	1			S3	S4	S5	S6	S8	S8	S9	S10	S11	S12	S13	S14	S15	S16
	2					S5	S6	S9	S9	S9	S10	S11	S12	S13	S14	S15	S16
	3																
	4																
	5	K1	K2														
	6			K3	K4												
	7					K5	K6										
	8							K7	K8								
	9									K9	K 10						
	10											K 11	K 12				
	11													K 13	K 14		
	12															K 15	K 16
	13	K 17	K 18														
	14			K 19	K 20												
	15					K 21	K 22										
	16							K 23	K 24	K 25	K 26	K 27	K 28	K 29	K 30	K 31	K 32

Table 5 Kites maintenance in workshop bays

Under the condition that the workshop is manned 7 days per week, the plan will allow for contingency efforts for unplanned workovers or tasks more time-consuming than anticipated.

In addition to the kite maintenance, the workshop/base must also be designed to provide ample resources and capacity for tether replacement campaigns each summer.

2.2 Identified Opportunities for Improvement

2.2.1 Increasing Rated Power of Kites

Increasing rated power of each kite would result in fewer kites in an array to achieve an 80 MW capacity in the Holyhead Deep site. To expand as an example, the 500 kW kite base cased is compared to a hypothetical 900 kW kite case. See Report [2] and Table 8 for practical information on what an installation would look like for different PowerKite kite cases.

For the 900 kW case, it would look like this:

- The number of kites in the array would reduce to 89 operational kites and 9 spare kites (reduced from 176 kites to 98 kites)
- Unplanned maintenance reduced to 8 kites/month (89 kites/12 months) conservatively
- 8 month planned maintenance program must absorb 64 unplanned operations during operational period
- 196 days available – 72 unplanned = 132 days remaining for planned activities
- 89 kites requiring planned maintenance to be undertaken in the 132 remaining days
- Sufficient to plan for one kite operation per day offshore
- Less sensitive to weather disturbances
- Workshop can spend more time on each kite and the workshop storage space can be reduced to 9 kites

The number of electric substations would be reduced from 27 to 15, assuming the onboard electrical equipment can adapt to the same number of kites delivering more power per kite.

There are consequences also to the sea floor cables, as more powerful kites render fewer components in the balance of plant.

2.2.2 Vessel Type, LARS Method, and Vessel Hours

The vessel type recommended is a DP2 Multi-cat vessel due to the flexibility, robustness, and versatility of this vessel. The operational strategy would need to be modified to use a vessel without DP2 capabilities. A faster vessel could also reduce operational time, but the most significant gain is to be made through improvement of kite handling procedures and techniques.

The LARS method can certainly be improved to be operational at rougher sea states, and to better handle multiple kites which would improve the operational procedure times and schedules. Improvement to the LARS strategy by reducing the time and complexity of operations would have most significant benefits to vessel operations and strategy.

The current assumption for a total of 7 hours turnaround is comprised of:

- 4 hours kite handling (2 hours on site and 2 hours in port)
- 3 hours transfer

Reducing this turnaround time will have several advantages, the most notable is being able to take advantage of narrow weather opportunities for operations. If the operators are confident that the operations can be executed quickly and safely, it increases the opportunities for launch and recovery activities, and it also reduces risk to the overall array operations.

2.2.3 Vessel Kite Storage and Handling Capacity

Operations would be best improved if it were possible to handle multiple kites on site. A vessel capacity or strategy which would allow a kite to be disconnected and replaced with a replacement kite without returning to shore would greatly improve operational times and complexity of maintenance strategy.

This is not possible with the recommended vessel. The operation procedure would need to be modified to accommodate this, or else a different ship would need to be used for this procedure. There are several options to explore, such as having a larger storage and handling capacity on the deck of the ship, towing the kites, or intermediate landing in water.

2.2.4 Manning/Planning Workshop Operations

Reducing the numbers of manhours required to perform the planned maintenance would improve the schedule for the workshop operations. Resource could then be reserved for significant unplanned work, for example repairing subassemblies.

2.2.5 LAR Operation Which Can Operate in Rougher Sea State

The current DG500 LAR (Launch and Recovery) operation has certain wave restrictions. This results in weather restrictions for operations as can be reviewed in Figure 5 Holyhead Deep Annual Down Time Due to Wave Height. Redesigning the LAR system or the LAR operations to withstand a higher maximum wave height would improve not only the length of the operational period for planned operation work, but also the amount of operational days within the available operational period. As mentioned in other sections of this report, such a new operational method has been identified and is being implemented for all coming kites.

2.2.6 Tether Maintenance and Replacement

Replacing and maintaining the tether every five years will generate around 30 operations every year for an array of 160 kites. This will generate offshore and onshore operations in addition to the kite maintenance. Extending the lifetime of the tether would be explored for such an array of kites.

3. Power Plant Maintenance

Following the assumptions outlined in section 1, a given kite must be maintained in seven days. This base case scenario requires workshop to operate seven days per week to accommodate the kite maintenance operations. The areas which have planned maintenance are identified, the workshop strategy expanded, and a spare parts strategy is discussed.

3.1 Planned / Periodic Power Plant Maintenance

The DG500 design which is the proposed kite for the PowerKite PTO within the scope of this report has the following components which requires annual intervention:

- Grease container replacement
- Lubrication oil replacement
- Drain seal system containers
- Replace hydraulic oil in control system (*)
- Replace filters in hydraulic system (*)
- Inspect bearings (various)
- Replace doller sensors
- Health check of back-up power supply systems
- Health check of hydraulic actuators
- Replace pitch rope
- Replace pitch rope fairings

(*) activities which require the hydraulic compartment (HPP) to be opened up. This activity will consume approximately 3 days as the DG500 nacelle must be opened, system resealed, and leak tested afterwards.

Kites will also require cleaning and must be inspected for coating damage. Coating repair may not be required annually, but manhours must be reserved for this work and the workshop must be prepared for this work if it is required.

Every five years, the following additional activities are required:

- Replace certain components inside power electronics in the Turbine Operating Module (TOM)
- Seal replacement turbine
- Replace hydraulic motors (refurbish)
- Replace hydraulic hoses
- Replace speed sensors
- Replace seals on hydraulic actuators

There is a risk that the 5-year planned maintenance activities cannot be performed within the 7-day allotted time period. One option is to swap the nacelle with a sealed and repaired nacelle. This would add cost to the spare parts list and require increased storage space. Another option would be to redesign the module breaks to improve nacelle repair procedures.

3.2 Offshore Handling Activities

Recovering the kite from the water to the vessel is a critical operation. The current operational practice for DG500 is to recover the kite from the water with a crane arrangement and using taglines to control the kite as it is lifted. The tether must also be disconnected and released. This operation requires a relatively mild sea state, crane, and a DP capacity vessel.

A new method of recovery allowing operations to be conducted in higher sea-states and with smaller vessels would yield a cost-effective operation and increase the accessibility of the kites throughout the year. Such a new method has already been identified, and is now being implemented in ongoing projects.

When this window is opened up sufficiently to allow for planned, periodic maintenance 12 months per year, the complexity and cost of the workshop operations can be reduced as well. This is expanded upon in section 2.1.7.

3.3 Workshop Handling Activities

Once a kite has been offloaded from the vessel and landed on the quayside, it is subject to the following operations:

- Quayside cleaning station
- Transportation to designated bay in the workshop
- Maintenance, repair, overhaul and other workover activities
- Testing (control system, hydraulics, etc)
- Re-coating (if required), if so in specific coating building/area
- Transportation to quayside

The workshop will have 16 bays, as well as areas for repainting, storage capacity for inventory, and workstations for work on subassemblies, from larger subassemblies such as nacelles to smaller and specialised components such as electrical units.

The workshop will have the capacity, training, and safety gear to do work at height, or have the capacity to raise and lower the kites beneath ground level for access.

3.4 Spare Part Strategy

A spare part strategy and inventory will be a critical part of the maintenance programme.

The following are a list of considerations which should be taken with a spare parts inventory:

- Parts which require replacement in planned maintenance
- Expendable parts, such as fasteners, O-rings, lubricants and grease, bearings, and other such components
- Parts with long lead time, which may be subject to non-planned maintenance activities
- Sub-assemblies which will require more than 7 days to repair should be maintained on separate workstations and maintained in the inventory
- New components or designs which will replace and obsolete old parts as the design is developed through new generations of kites
- Parts with low MTBF (Mean Time Between Failure)

The Kite is comprised of many subassemblies. If the workshop has capacity, in both space and budget, it would save time to work on subassemblies separate of kite repairs in the bay and swap the assemblies in and out of kites. A list of some of the larger sub-assemblies is as follows:

- Hydraulic Power Pack (HPP)
- Distributed Power Module (DPM)
- Turbine Operating Module (TOM)
- Rudder and Elevator Housing (REH)

Other components which are not part of regular replacement program, but needs to be available in the event they fail or get impacted during handling – referred to as capital spares in this context – are also required. Exact quantity of such spares is a combination of lead time, anticipated failure rate and cost of component. Typical capital spares with estimated lead times for reference would be:

- Generator
- Gear box
- Rudders and elevators
- Struts
- Turbine and shaft

Wing is considered repairable to an acceptable level until a spare wing can be provided. In an array scenario there will be capacity in the supply chain to deliver wings relatively quickly. This also applies to rudders and elevators, but these are much cheaper and easier to store being much smaller than the wing.

3.5 Areas of Improvement to Power Plant maintenance

3.5.1 Executing Periodic Maintenance Offshore

Maximizing the maintenance which can be executed offshore will have a significant impact on the operational aspects and economics of an 80 MW array.

Offshore work does not require disconnecting the tether from the kite. They could be captured from the surface, maintained, and released immediately upon completion of maintenance. Table 6 Duration of Offshore Maintenance in Slack Water shows such a plan for maintenance performed on two kites. Assuming this operation can be executed in two hours per kite, two kites can be serviced in each slack water / no-production period, resulting in no loss of production.

Activity	Duration (Minutes)
Drive to location	60
Crew transfer to buoy	30
Recover kite	15
Offshore maintenance	120
Relaunch kite	10
Drive to next location	10
Recover kite	15
Offshore maintenance	120
Relaunch kite	10
Crew transfer from buoy	30
Transfer to base	60
Total duration (minutes)	480
Total duration (hours)	8

Table 6 Duration of Offshore Maintenance in Slack Water

As the slack water periods are shifting over time, operations must accept that kites are being maintained also during production periods. With this mindset, a vessel could then expand operations to up to 12 hours and maintain three kites per day as shown in Table 7.

Activity	Duration (Minutes)
Drive to location	60
Crew transfer to buoy	30
Recover kite	15
Offshore maintenance	120
Relaunch kite	10
Drive to next location	10
Recover kite	15
Offshore maintenance	120
Relaunch kite	10
Drive to next location	10
Recover kite	15
Offshore maintenance	120
Relaunch kite	10
Crew transfer from buoy	30
Transfer to base	60
Total duration (minutes)	635
Total duration (hours)	11

Table 7 Duration of Offshore Maintenance Per Day

According to assumptions derived in section 172.1.7, there are 90 days available for planned maintenance. If the planned maintenance can be performed offshore, it would reduce the maintenance of 160 kites to 50 days. This would provide generous contingency for weather restrictions, maintenance planning of other objects, and unplanned maintenance activities.

3.5.2 Struts

To assist and ease all activities in the workshop, the struts must be designed for fast detachment and re-attachment. It would benefit operations if the struts can be left connected to the tether and remain offshore as a kite without struts will be much easier to handle in the workshop areas.

3.5.3 Connection and Disconnection

Improving accessibility and speed of connecting and disconnecting operation could result in both faster operations as well as increased sea state availability for operations. The modified joints would be compact with low drag. Remote connection or disconnection could also be explored.

3.5.4 Modular Breakdown of Power Plant

It must be possible to isolate and remove any module in the power plant without having to remove any other module first. If this is impossible to achieve, the operation of removing another module must be swift and easy, without having to break out hydraulic connections or other pressurized components.

Having the ability to simply replace a faulty module and replace with a fresh one will improve maintenance turnaround times. Modules could either be repaired on site or be shipped to supplier for refurbishment.

3.5.5 Improving Service Intervals

With continued improvement to the designs, the service intervals can be reduced. For example, the tether currently has a 5-year design life. This technology is new and unique to Minesto, so it is not unreasonable that over the lifetime of the kites that the tether life can be improved and expanded to result in fewer planned maintenance. Improving the design life the parts could reduce planned maintenance from every year to every 18 months, 2 years, or even 5 years.

4. Array Components Maintenance

The Array components have a low overall impact from the OPEX according to the LCOE calculations; nevertheless, minimizing the amount and complexity of the array components would reduce and simplify the component maintenance strategy and planning. Any opportunities for improvement are expanded upon below.

4.1 Maintenance of Electrical Equipment

Each substation holds various electrical equipment, such as low and high voltage transformers and low or medium voltage switchgears. Transformers have an excellent service life compared to switchgears, and therefore no scheduled replacement work is planned for these components. They would need to be replaced in non-planned maintenance in the rare case of a catastrophic failure.

Switchgears are at a higher risk of failure; as a result, they are built up by rack modules which can be replaced on location. This operation, as with all electrical systems work on the buoy, requires the electrical system to be shut down and positively locked out.

An annual inspection program for each TMS is included in the base case scenario, but as the buoy is visited every time a kite is to be connected/disconnected it is recommended that the operator then conducts a routine inspection as part of the operational procedure. Every six years the TMS buoy is subject to a major inspection, which includes replacement of electrical components as defined by the program. The TMS would be inspected to at least a bi-annual level through a planned inspection programme.

The buoy-to-buoy connections, visualized as a red line in Figure 1, are designed in the base case array such that each buoy can be disconnected without interfering operation on any other buoy.

4.2 Maintenance of Marine Equipment

An installation in the sea will require consistent maintenance. The TMS buoys are designed for the full operational life of 25 years. The buoys will be manned intermittently, which adds safety requirements to the operational programme.

The amount of time and operations which must be performed on the buoy will be minimized. Manning the buoy changes the regulations and classification of the buoy. This base case report assumes that the maintenance activities of the buoys can be addressed during the 1-year and 5-year periods as defined for the electrical onboard equipment.

In addition, the buoys are boarded every time a kite is being serviced. Lighter service and inspection can be executed on such visits.

Maintenance of mooring system also requires retensioning of the mooring lines.

4.3 Areas of Improvement to Array Component Maintenance

Reducing the complexity of the TMS buoy by minimizing the equipment on board will improve the operational and maintenance strategy, most notably by reducing the manhours of on-board activities. If the Buoy requires too much service, operation, or inspection by manned personnel it will change the definition and requirements from an intermittently manned to a manned installation. This greatly complicates safety equipment, requirements, planning, and strategies so it would be avoided.

In addition to simplifying and reducing the time on board the Buoys, reducing the number or buoys or replacing the buoys with an entirely unmanned alternative are the next areas of improvement. It should be possible to swap out the TMS solution if it were more compact than a buoy, which would further improve the LCOE of the technology. Such a TMS solution would be more flexible for smaller arrays and installations as well.

The cables and electrical components could also be individually investigated to determine if improvements could be gained through upgrading or modifying the existing components.

5. Array Evaluation and Comparison

The cases which are analyzed are included below in Table 8.

Table 8: Array Evaluation and Comparison

PowerKite concept alternative No.	Array Case No.	Kite Power (kW)	Array Power (MW)	Voltage	Grid	Number of Kites	Cable Array Table
PK1	1	500	78	500V	Base case	156	1
	2	500	78	690V	Base case	156	2
	3	500	78	3000V	Base case	156	3
PK2	4	900	81	690V	Base case	90	4
	5	1500	81	2200V / 3000 V	Base case	54	5
	6	500	72	500V	Seabed Trafo + Hub	144	6
	7	500	72	690V	Seabed Trafo + Hub	144	7
	8	500	72	3000V	Seabed Trafo + Hub	144	8
PK3	9	900	72,9	690V	Seabed Trafo + Hub	81	9
PK4	10	1500	72	2200V / 3000 V	Seabed Trafo + Hub	48	10

Operationally, the biggest difference between the powerplants are the size and weight of the powerplants, and these will be the most significant considerations with respect to operational procedures. A more powerful kite will most likely have a larger wing plan area, but the overall physical size of the power plant does not necessarily have to change.

There will not be one optimized size or design. The optimal size of kite will depend on the individual site, the operational capabilities, and other factors. The array concepts are compared for installation, maintenance, servicing, inventory and vessel, workshop, and office selection and requirements.

5.1 Installation

The base case kites (case 1 and 6) are identical to the current DG500 prototype and will require similar methods for installation as DG500 such as using a DP vessel, unless the operation concept is modified or the base case kite modified for array development. For all other cases, the new handling method will be implemented which includes towing kites to/from site, which will reduce the requirements on vessel capacity. Further, should a development of 500 kW instead of more powerful kite be decided upon, these kites would also be designed for towing operations rather than lifting.

For cases with a lower number of kites, the amount of operations will be lower as well, not just for kites but also tether maintenance.

The TMS will require a DP vessel for installation. The seabed trafo may require a DP Vessel for installation and retrieval operations. The seabed hub is designed to be installed with a 28-metre Multicat.

5.2 Maintenance and Servicing

There is an assumption of one planned and one unplanned maintenance or service operation per kite per year, independent of the version of the kite; as a result, the larger kites will imply fewer operations as there are fewer kites in the array to produce 80 MW.

The workshop will also need fewer bays, perhaps slightly larger ones but wing span is maintained as this is driven by the Holyhead Deep water depth limited the impact from the wing. Inventory for parts will require equal or less space for the larger kites, as spares are mostly associated with non-structural components, and the structural components are the large ones. Certain parts, in particular capital spares, will be more expensive to replace, but many of the other components are similar between the various cases. Shipping larger components can also be restrictive, but even the DG500 wing requires escort transportation if on road. It is not unrealistic for a Holyhead Deep site case to either utilize the railroad which extends into the harbour, or even sea transportation – so the shipping issue is not anticipated to become an issue even for more powerful kites.

There will be fewer kites in inventory than the smaller kites.

Tools, stands, equipment and other utilities for kite maintenance are anticipated to be equal between the cases.

Total inventory could be smaller for larger kites due to smaller array size, but the mandatory inventory for long lead time parts which are not part of regular replacement program but in place for contingency, is similar for all array sizes and the cost of these parts increase along with kite power. The space required to store the parts also increases with the size of the kites and requires a larger inventory space as well, unless storage is kept with component supplier which is an option (for all cases).

The 500 kW kites will require more frequent maintenance trips due to there being more kites in the array to produce the desired output. These kites would be towed as well, as mentioned in the section above. Vessel size is expected to be reduced, compared to the DG500 prototype, with the new handling method, applies to all cases.

The buoys can be maintained and serviced, but with 27 of them it will be a relatively large effort. Buoys would require replacement inventory, and possibly modules or sub-components prepared and stored.

Seabed hubs and seabed transformers do not require maintenance, but do require entire units to be built and stored in the case that one would need to be swapped in the event of malfunction. Consequently, spare components and assemblies must be readily available near the site. Transformers are statistically not prone to failure, so the number of spare transformers can be kept to a minimum.

Unless designed for properly, subsea replacement operations are expensive, weather restricted and potentially time-consuming, especially if mobilizing a DP Vessel are required for these operations.

Office size should not be greatly impacted by array size and type.

6. Cost Analysis

The different array alternatives are compared with regards to strategies and cost impact of the investment, installation, service and maintenance of the power system.

As with the previous section, the cost is dependent on: site location, array implementation, and kite size and type. The cost of staff, petrol, and both onshore and offshore equipment and services is tied to the local economy of the site and timing of the array implementation. Since cost is tied to each operation or day of operational work, and there are fewer operations required for fewer kites, the cost is nearly linear reduced with respect to installation, service, and maintenance costs with increased power in kites as there are fewer kites required to produce an 80 MW array.

The cost model below includes all components that build up the array; however, regarding the capital costs, only the power array system costs are included. Notably, the capital cost for the kite, tether, bottom joint and foundation have been excluded to focus the evaluation on the array system and make cost differences between the array power systems clearer.

6.1 Capital and Installation Costs

The kite power, and the annual energy yield that is closely linked to it, has the biggest impact on array costs as shown in Figure 6. For a given array of 80 MW, the number of kites, cables, and components reduce with increased kite power, which reduces the capital and installation costs. This is observed for the base case and the seabed solution, and it is also true both for Capex and Opex.

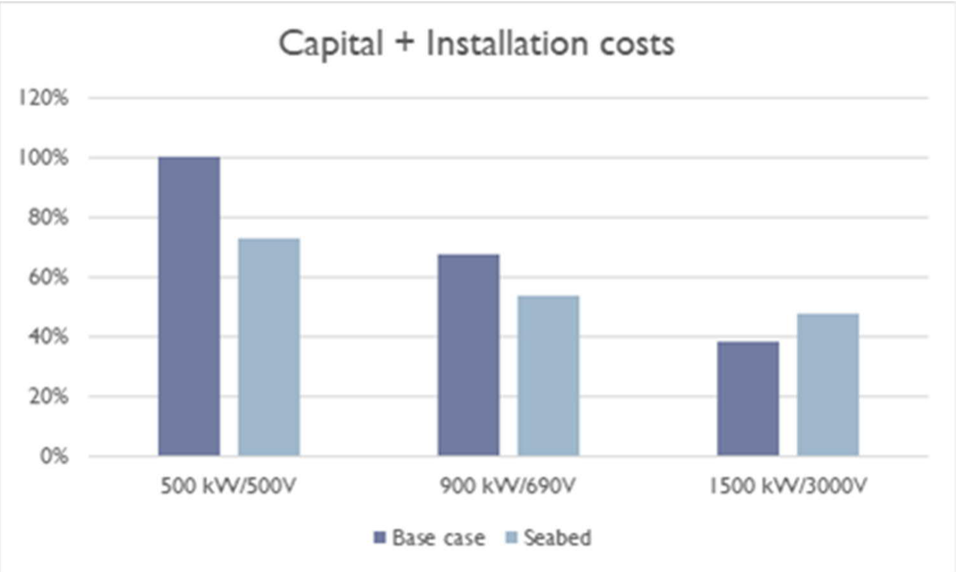

Figure 6: Comparison of Sum of Capital Costs and Costs for Installation

Both the Buoy and the smart hub require hiring additional vessels as the long-term contracted 32-metre DP vessel used for kite operations is insufficient for installation of these components. The seabed transformer would require a 50-m DP vessel, the seabed switchgear a 28-m Multicat, and the Buoy would require several tug boats to install. The foundations also require special vessels for installation.

6.2 Ongoing Operational Costs

The service and maintenance costs are dependent on the hours required to perform the operations.

Much like the installation cost for the kite, the operational costs for servicing and maintenance is pinned to the cost of each operation, and fewer planned and unplanned operations are predicted for a smaller fleet of higher voltage kites which can be observed in Figure 7. The impact of using tow method for kites have not been included in the below cost comparison, as the costs are relatively low compared to other elements. But when implementing this method, the cost will become lower, so consequently the below is a conservative approach.

The operational costs are lower for the Seabed solution due to the lack of annual operations required for the seabed solution. The foundation is not predicted to have any operational or maintenance operational costs.

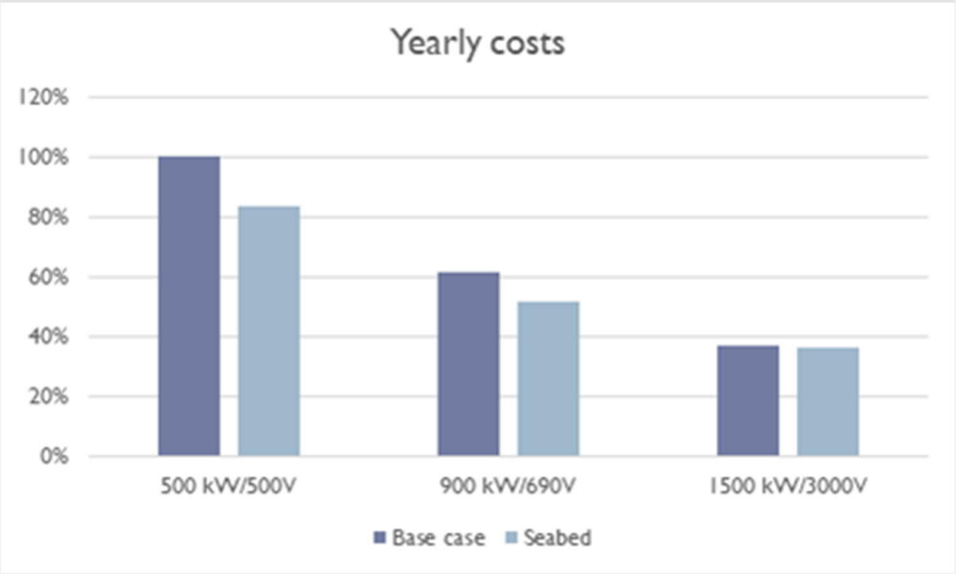

Figure 7: Comparison of Sum of Yearly Costs for the Array Power Systems.

6.3 Array LCOE

The Array LCOE is shown in Figure 8. Raising the system voltage reduces the LCOE for the base case significantly. The difference between the base case and the seabed solution is much smaller for a 3000V kite. It should be noted that a 3000V electric drive will represent a costlier kite.

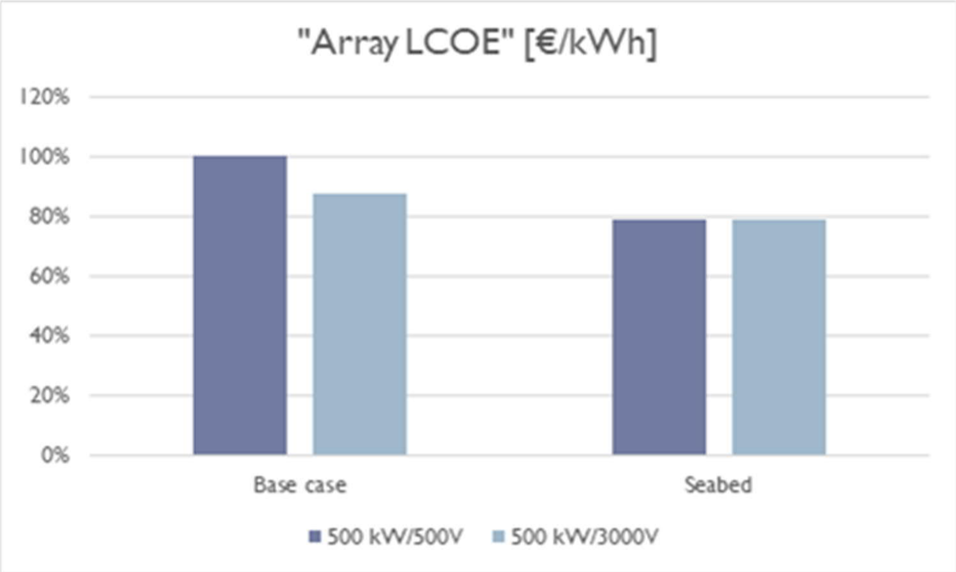

Figure 8: Array LCOE Base Case and Seabed

For the estimated levelized cost of energy for the array, the costs for the seabed solution is approximately 80% of the base case for 500 kW kites (Figure 9). It can be observed that the difference decreases with the larger kites, and for the 1500 kW alternatives the cost is similar for both solutions. With the assumptions made in this study, the costs for the array measured as LCOE is only 25% for the 1500 kW kite arrays as compared to the 500 KW base case.

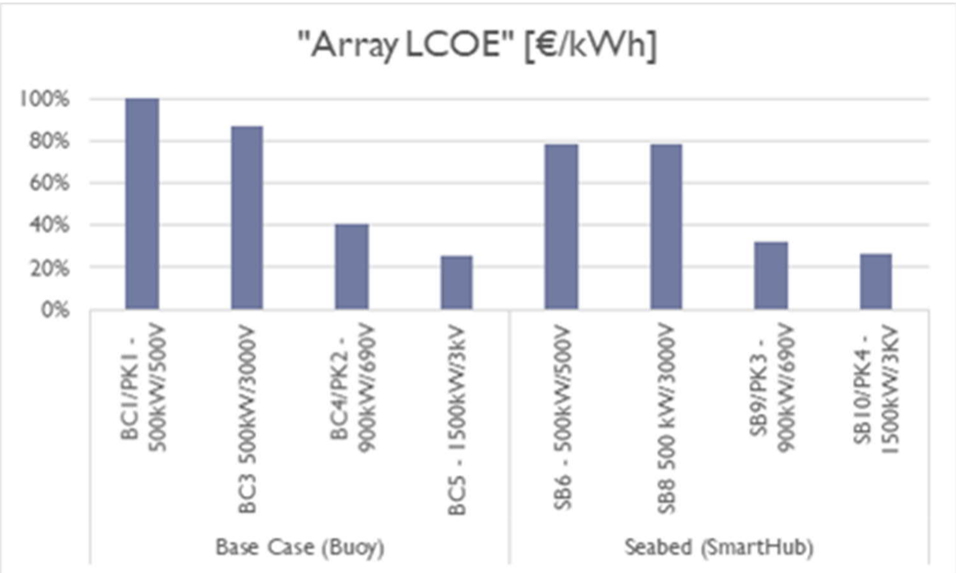

Figure 9: Array LCOE Estimation for the Array Power Systems

6.4 Kite CoE

The kite has not been considered within the scope of the cost analysis for the capital costs. This decision has been made in order to focus the study on the evaluation of the array system. See Report [3] for information on the Cost of Energy of the kite.

Conclusions

A maintenance strategy has been developed for an 80 MW array of 500 kW kites at the Holyhead Deep site in Wales. The base case also contains foundations, TMS, and other array components such as cables. This report also explores areas of improvement of the suggested strategies. This strategy is also discussed with respect to additional PowerKite cases.

A cost model was built up to evaluate and compare the array power system designs developed. The cost model was also linked to the future development of the kites by evaluating the impact of two additional kite designs that were results of a kite optimization study. This required some extrapolation of the base case array design to accommodate the higher power produced while retaining the conceptual design.

The study shows that from the array perspective, the increased power of the optimized kites has a very strong and positive impact on both Capex and Opex for both array alternatives studied.

Further, optimization of marine operations, for example the new method which is towing the kites rather than lifting them will further improve the operations. The impact from this modification, as well as to other parts of the installation and operation of the balance of plant, are not included in this report but underlines that there is room for further improvement.

When comparing the impact of the kite generator voltage, increased voltage has a large positive impact on the cost for the base case array solution but minimal impact on the seabed solution. The base case is very much limited by the kite generator voltage, but the seabed solution comprises a seabed transformer for each kite that minimizes the impact of the kite voltage.

When comparing the array power system solutions, it is important to include the time scale in the discussion. The base case solution was developed from the development status at the start of the PowerKite project with the assumption of using existing components and be independent on additional technological development that is difficult to predict or evaluate.

The seabed solution is much closer to a desired future solution that a) has minimal need for maintenance and repair and b) has all the components on the seabed and thus no visual impact and minimal interaction with activities on the sea surface. During the project, a semi-commercial product, the “SmartHub” presented by ETA has entered the market, which in many aspects fits this development path. However, it is important to notice that some required functions for the array power systems do not yet have a solution for the seabed solution, so further development is needed before an installation could be performed.

The cost model does not cover all part of a full production site, but is focused on the main part of the array power system. It is believed that with some further development and extensions, the cost model could be a useful tool for Minesto to perform studies to give input to the development of future solutions with optimized LCOE.

Upon reviewing the data collected from the Holyhead Deep site, it was determined that the wave height was the most critical aspect that determines the service windows for the marine operations. The weather modeling has been valuable as a prospective tool for future planning.

References

[1] PowerKite iD5.2l, Weather Window Analysis Report, Dr. Louise Kregting, 2018
[2] Powerkite Report D5.1, Commercial Power System Design Report, Per Salomonsson, 2019
[3] Powerkite Report D7.11 Cost of Energy Impact Assessment Report, Michael Rösman, 2018

Information on EU funding / Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654438.