RISK ASSESSMENT FOR THE INSTALLATION AND MAINTENANCE ACTIVITIES OF A LOW-SPEED TIDAL ENERGY CONVERTER

I Lazakis and **O Turan**, Department of Naval Architecture & Marine Engineering (NA-ME), University of Strathclyde, Glasgow, UK
T Rosendahl, Minesto UK Ltd, Belfast, UK

SUMMARY

The study presented in this paper, is part of the Deep Green project, which includes the development of a power converter/device for employment in low-speed tidal currents. It mainly focuses on the initial steps to investigate the ways on how to minimize the risks during handling, operation and maintenance (O&M) activities of the full-scale device particularly in offshore operations. As a first step, the full-scale device offshore installation and O&M tasks are considered. The overall risk analysis and decision making methodology is presented including the Hazard Identification (HAZID) approach which is complemented with a risk matrix for various consequence categories including personnel Safety (S), Environmental impact (E), Asset integrity (A) and Operation (O). In this way, all the major risks involved in the mentioned activities are identified and actions to prevent or mitigate them are presented. The results of the HAZID analysis are also demonstrated. Finally, the last section of this paper presents the discussion, conclusions and future actions for the above-mentioned activities regarding the full-scale device.

NOMENCLATURE

ABS	American Bureau of Shipping
DNV	Det Norske Veritas
DP	Dynamic Positioning
EIA	Environmental Impact Assessment
EMP	Environmental Management Plan
E/R	Engine Room
EU	European Union
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FTA	Fault Tree Analysis
FSA	Formal Safety Assessment
GL	Germanisher Lloyd
HAZID	Hazard Identification
HAZOP	Hazard and Operability study
HSE	The UK Health and Safety Executive
IMO	International Maritime Organisation
MARPOL	IMO Maritime Pollution convention
MOB	Man Overboard
MSDS	Material Safety Data Sheet
NAME	Dpt of Naval Architecture & Marine Engineering
NORSOK	Norsk Sokkels Konkuranseposisjon (Norwegian Offshore Sector)
PPE	Personal Protective Equipment
RBD	Reliability Block Diagrams
ROV	Remotely Operated Vehicle
SJA	Safe Job Analysis
SOPEP	Shipboard Oil Pollution Emergency Plan
VHF	Very High Frequency

1. INTRODUCTION

Ocean energy (wave and tidal) has the ability to supply more than 50 percent of the world's electricity demand. Estimates made in 2006 demonstrate an electricity generation potential of more than 800 TWh per year for tidal power [1]. The above potential may be increased especially in areas which favour the operation of devices in low-stream tidal velocities. These areas have not previously been included in external market estimations since no viable technology existed for the low-velocity range. This issue has been addressed with the development of the innovative Deep Green project by using the Seakite, a novel device which is used to produce power from low stream tidal currents. The Deep Green technology has been estimated to provide the total electricity generation up to 300 TWh per year, which is equivalent to the electricity consumption of 48 million households [2].

This paper presents the initial study regarding the Deep Green project; that is the minimization of the risks during handling/installation, operation and maintenance activities, particularly in the offshore environment. As a first step, the single Deep Green installation and operation are assessed. A thorough review and examination of the past and current risk analysis methods in the offshore renewables and oil and gas sectors is carried out in section 2 in order to achieve the optimum methodology for implementation in the proposed innovative tidal energy convertor design. The overall risk analysis and decision making methodology is presented in section 3, including the HAZID approach which is complemented with a risk matrix for various consequence categories. A specific description of the single Deep Green device with its components is explained and demonstrated in the same section. Section 4 presents the results of the HAZID analysis including the potential high-risk areas. The discussion, conclusions and future actions to be followed on the current study are finally shown in section 5.

2. LITERATURE REVIEW

The subject of risk analysis, risk assessment and overall risk management is a widely explored field with various studies contributing to its thorough examination. Particularly in the maritime and offshore oil and gas industry, risk analysis has developed significantly to ensure the safety of personnel employed, the protection of the environment and the reliability of the asset involved (either ship or offshore platform). Moreover, it has been used to highlight the operational excellence of the mentioned maritime and offshore activity (although in some cases, procedures have been accelerated after the occurrence of disastrous accidents).

The UK Health and Safety Executive (HSE) pioneered in the development of such procedures addressing risks in their overall conception by introducing the Safety Case approach in 1992 [3]. In it, guidelines are given on what operators of each offshore installation need to do in order to "reduce the risks from major accident hazards to the health and safety of the workforce employed on offshore installations or in connected activities". In this case, the owner or operator of the installation needs to prepare a safety case report and submit it to the HSE for approval.

In order to strengthen this effort, the ALARP concept was also initiated in 1999 in an attempt to suggest measures to reduce risk "As Low As Reasonably Practicable" [4]. This concept is based on the ranking of risks from unaccepted to tolerable and finally broadly accepted levels measured by individual and societal concerns. If there are any risks in the unaccepted level, the related activity is abandoned and reconsidered so that the risk can be reduced to a satisfactory and controlled level. Furthermore, the Norwegian petroleum industry developed the NORSOK standard Z-008 [5], which provides guidelines and requirements for the implementation of maintenance programs for new and in-service facilities both offshore and onshore regarding risks related to personnel, environment, production loss and direct economic cost.

The OREDA handbook [6] was another effort originating from oil operators to enhance the maintenance and operation of offshore structures by collecting data for the topside and subsea equipment. Various other efforts also address the issue of risk analysis and assessment of hazards. The reader of this paper is indicatively referred to the common BS/ISO 17776 standard for the petroleum and gas industries [7], the marine risk assessment offshore technology report prepared by DNV for the UK HSE [8], the EU funded SAFEDOR project deliverable D4.5.2 [9]. Additionally, further studies refer to the IMO FSA approach [10], the DNV recommended practice on risk management in marine and subsea operations [11] and the ABS guidance notes on risk assessment applications for the marine and offshore oil and gas industries [12].

In the sector of offshore renewables, a combination of the risk methodologies mentioned above with the particular characteristics of the renewables field has been applied. DNV initially generated a report for the UK Carbon Trust setting guidelines to be followed on the design and operation of wave energy converters [13] as well as developed the offshore service specifications about the certification of tidal and wave energy converters [14] and performance criteria determined from the risk assessment methodology [15]. Various other research studies on offshore renewable energy devices include among others the work on wave energy converters [16], [17] and marine current turbines [18]. All the above show in the most explicit way the development carried out in the offshore renewable field in the last few years as well as the promising outcomes to be generated in the near future. With all this in mind, the section that follows next presents the risk analysis and decision making methodology suggested for implementation on the Deep Green project.

3. METHODOLOGY

In this section of the paper, the suggested risk analysis and decision-making methodology is presented (Figure 1). As is shown, the first step is to define the key activity areas in order to establish their boundaries and constraints in which the potential hazards will be identified. In this case, the key activity areas are the offshore installation and operation of the Deep Green device.

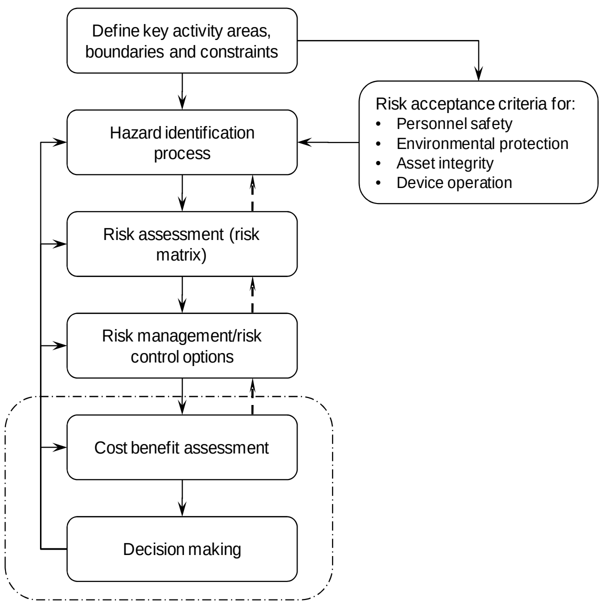

Figure 1: Risk analysis and decision making methodology

After this stage, the risk acceptance criteria are described in order to enable the analyst to compare the hazard identification results with a set of pre-described values. After this level, the core part of the risk analysis can take place. Initially, the full hazard identification process is employed to list all the potential undesired events, which may impede the mentioned key activities (i.e. offshore installation and operation of Deep Green). This leads to the risk assessment stage, which may be either qualitative or quantitative. A number of different tools may be used such as the well-known FTA, ETA, FMEA and FMECA, the development of risk matrices, the Markov Analysis tool, RBDs, HAZOP and other available well established tools provided for examining the risk ranking, the reliability and availability of the examined system and sub-systems.

After the identification and assessment of the potential hazards, the risk management stage takes place. In this case, the higher ranked risks are dealt with in terms of designing-out the potential hazards in the initial stages of the device, preventing the hazards from occurring, mitigating the effects of the hazards in case they occur or finally be pro-active for emergency response actions. The measures taken are then assessed regarding their cost-benefit value and eventually a decision is considered of whether to apply the specific risk control option or not. The final decision is then used in the feedback loop to update the other steps of the risk analysis mentioned before, improving the results and minimising any gaps identified in the process. It is important to mention that the updating and feedback procedure occurs throughout the risk analysis in order to develop a complete and systematic examination of the system under consideration.

Bearing the above in mind, the Deep Green hazard identification approach is explained with more details in the following section.

3.1 DEEP GREEN HAZARD IDENTIFICATION APPROACH

3.1 (a) Brief description of the Deep Green device

In order to achieve the Deep Green hazard identification approach, a brief description of the technical characteristics of the device is presented based on the information gathered from the initial concept design stage.

The Deep Green device is designed as a moving underwater power plant, which will be optimized to produce energy from low-speed tidal streams. By a reliable control system it moves on an eight shaped trajectory of about 300m length. The lift produced by the wing and its movement drives the turbine, which powers the generator. With a tidal current speed of 1.7 m/s, the wing will move with a speed up to 17 m/s. The power will be transmitted through a cable integrated in the wire to a terminal at the seabed, which will be connected to the shore. The overall weight of the device is expected to be 7 tons. In Fig. 2, the initial design of the overall device is shown.

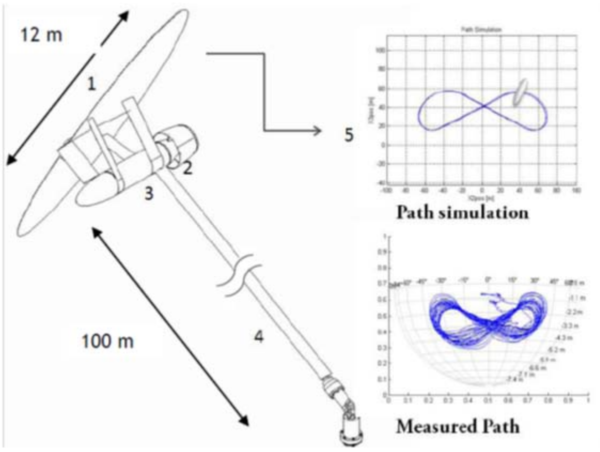

Figure 2: Deep Green device initial design concept and main components

As can be seen, Deep Green consists of three major parts:

1. The wing (1)
2. The nacelle (3) and
3. The tethering system (4)

The wing has a span of 12 m (chord 2.25 m, thickness 0.3 m) and includes a set of equipment and parts such as a set of batteries for redundancy control, the buoyancy system as well as the struts that connect the wing with nacelle. The nacelle houses a turbine and a 0.5 MW-generator used to produce the power required. It also includes a rotor (2), which has a diameter of 1.2 meters and rotates at 750 rpm. Behind the rod, a rudder is mounted. The device is connected to the ground by a tethering system (4) including several single-tether pieces and a swivel as part of the seabed foundation. A Quick Release Mechanism (QRM) is used as the connecting point between the two main struts supporting the wing and the tethering system. It is placed at a distance of about 10m from the top of the wing providing a safe and a secure point in case the device needs to be detached from the tethering system for retrieval and maintenance. The Deep Green device will be able to operate in water depths of 60-120m with a water depth clearance of 15m from the surface of the sea when in operational condition. Having all the above in mind, the presentation of the Hazard Identification (HAZID) approach is shown in the next section.

3.1 (b) Development of risk matrix

In this section, the development of the risk matrix that is employed for the HAZID approach is presented. In this respect, various studies on the development of risk matrices have been reviewed, among others the study of [7], [10], [14] as well as the work of [17] and [18]. A consequence as well as a probability Table is developed showing the various levels of consequence and probability rankings accordingly. For the formation of the consequence Table, four different areas are considered. The potential risks for each one of the different risk affected areas are ranked into five categories: A (minor), B (marginal), C (major), D (critical) and E (catastrophic) as shown in Table 1.

Table 1: Risk consequence categories

Consequence	**Personnel safety**	**Environmental impact (recovery time)**	**Asset integrity**	**Operation**
A (minor)	no injury	no damage/contamination	negligible damage < 2k £	minimal operation loss
B (marginal)	minor injury (first aid)	minor damage/spillage, good effect of control measures (a few days)	minor damage 2k - 20k £	short operation loss (few hours)
C (major)	multiple minor injuries, major injury	major damage/pollution, low effect of control measures (a few days to a month)	localised damage 20k - 100k £	minor replacement needed (operation loss < 1 day
D (critical)	multiple major injuries	critical damage/pollution, minimal effect of control measures (more than a month)	major damage 100k-3M £	major repair needed (operation loss 1 day-week)
E (catastrophic)	1 or more fatalities	Significant environmental impact, massive pollution (more than a year)	damage >3 M, total loss	total operation loss, replacement

Regarding the consequences categories, it is assumed that one major injury is equal to 10 minor injuries while one fatality is equal to 10 major injuries. In terms of the probability ranking, it is divided into five categories: 1 (extremely unlikely), 2 (remote), 3 (occasional), 4 (probable) and 5 (very frequent). The probability ranking is carried out in terms of the entire project and of a single device as well bearing in mind that the full project scale includes an array of 30 devices while the operational lifespan of each device is assumed as 20 years. Based on the above, the quantitative probability ranking is shown in the last column of Table 2.

Table 2: Risk probability categories

	Ranking	**Description**	**Quantification**
1	extremely unlikely	1 event/project lifetime	1.39E-04
2	remote	several events/project lifetime	4.17E-04
3	occasional	1 event/device lifetime	4.17E-03
4	probable	several events/device lifetime	4.17E-02
5	very frequent	1 event/device month	4.17E-01

It is important to notice that the quantitative values for each one of the ranking levels are derived from following equations:

$$P = 1 / D \quad (1)$$

$$D = 12 * T * N \quad (2)$$

where:
P = probability
D = duration (in months)
T = active operational time of a single device (years)
N = envisaged number of devices employed in the full-scale project (20 devices to be employed overall)

Having all the above in mind, a risk matrix is developed related to the previously mentioned areas in order to provide the ranking of the potential hazards as well as identify their risk level. Overall, risk ranking is identified as the outcome of consequence and probability of occurrence of the mentioned consequences. Table 3 presents the suggested risk matrix showing the four distinctive areas of risk ranking.

Table 3: Risk matrix for the Deep Green device

	Probability				
Conseq	**1**	**2**	**3**	**4**	**5**
A	A1	A2	A3	A4	A5
B	B1	B2	B3	B4	B5
C	C1	C2	C3	C4	C5
D	D1	D2	D3	D4	D5
E	E1	E2	E3	E4	E5

As shown, four risk levels have been created. These are defined as low, moderate, significant and high (Table 4).

Table 4: Risk index table for the risk analysis of the Deep Green device

Risk index table	
Level 1	Low (negligible risk)
Level 2	Moderate (tolerable risk)
Level 3	Significant (tolerable, specific measures in place)
Level 4	High (intolerable risk)

- Level 1: Low (negligible risk)
- Level 2: Moderate (tolerable risk)
- Level 3: Significant (tolerable risk with specific measures in place to prevent/mitigate the potential risks)
- Level 4: High (intolerable risk)

The risk matrix is developed in such a way as to demonstrate the various risk levels involved in this innovative power generation project. At this point it should be mentioned that the last level (Level 4: intolerable risk) has been expanded to include all cases in which, risk of one or more fatalities is present (boxes E1 and E2) to emphasize the importance of it. Bearing the above in mind, the presentation of the overall HAZID process follows next.

3.3 HAZID presentation

In this section, the Hazard Identification (HAZID) for the offshore installation, operation and maintenance activities of the Deep Green device as well as of the Deep Green project are shown. For a complete representation of all the potential risks involved in these activities, the direct as well as the indirect hazards are analysed. Direct hazards involve the ones directly related to the Deep Green such as lifting operations, occupational and health hazards, operation of ROVs etc. Indirect hazards involve the ones related to the overall installation activity including the installation vessel and its crew (e.g. fire on board the vessel, hot weather, etc.) bearing in mind the operational environment of the Deep Green in a worldwide context. In these terms, the following areas are examined for the installation phase of the project:

1. Lifting operations offshore
2. Seakeeping
3. Vessel stability
4. Other vessel in the vicinity
5. Floating device/equipment
6. Operation of ROVs
7. Occupational hazards
8. General health hazards
9. General environmental hazards
10. Fire
11. Construction works (foundation, etc.)

For the operation phase of the project, the complete/partial loss of operation of the device is examined separately. For the maintenance activities of the project, the Deep Green device is examined together with any other activities related to it such as lifting operations, occupational and health hazards etc. In this case, the hazards identified as well as the potential risks and the proposed mitigation measures are similar to the ones identified for the installation offshore activities. The above are summarised in Fig. 3.

In addition to the above, for each one of the different areas/topics identified, all the potential hazards (what can go wrong?) are listed. Furthermore, each hazard is investigated in terms of the following:

- Cause (why can it go wrong)
- Consequences of mentioned hazard (which are the end-results)
- Consequence index
- Probability index
- Overall risk index
- Risk control options
- Remarks

The consequence, probability and consecutively the risk index are examined in terms of:

- Personnel safety (S)
- Environmental protection (E)
- Asset integrity (A) and
- Device operation (O)

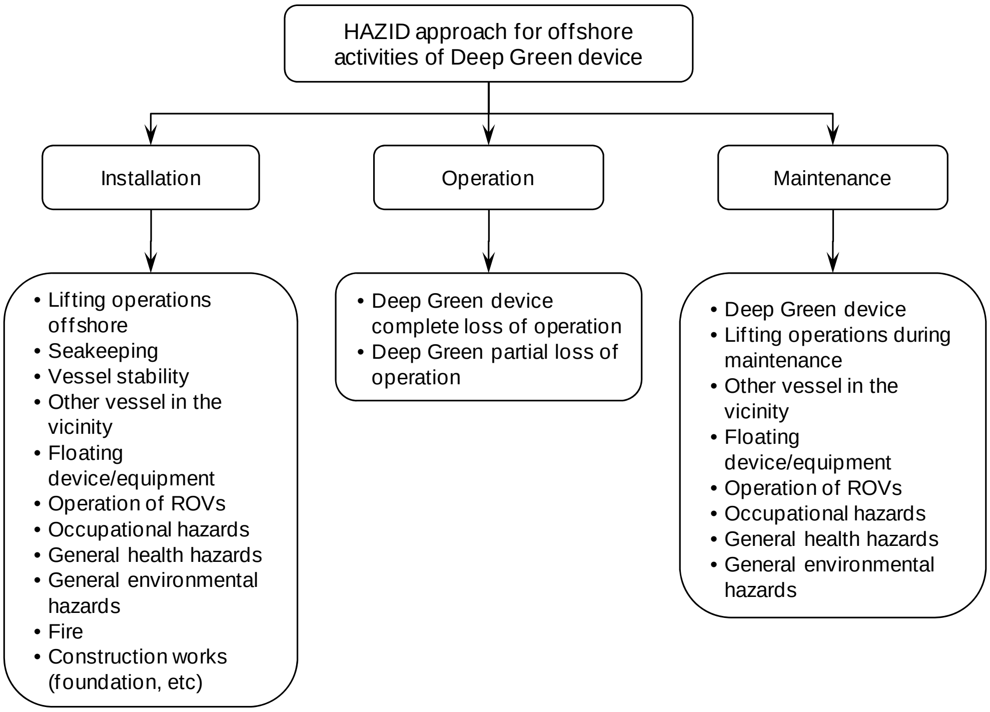

Figure 3: Summary presentation of the Hazard Identification (HAZID) for the offshore installation, operation and maintenance activities of the Deep Green device

Bearing in mind all the above, a part of the HAZID approach is shown in Table 5 while the full detailed HAZID process for the offshore installation, operation and maintenance activities is fully demonstrated in [20].

Furthermore, although it is envisaged that divers will not be employed during the installation and construction works of the full scale device (as well as for the entire Deep Green project site) in order to reduce hazards and associated risks, commercial divers may be utilized in the installation activities of the 1/10 scale model device. In this respect, diving operations will be carried out at shallow water depths. Although the aforementioned diving operations will not require saturation diving procedures and equipment and accordingly will not necessitate the corresponding safety measures taken and related hazards identified, a HAZID analysis has been performed for the shallow water diving operations executed. To this end, [20] describes the hazards originating from the referred diving operations.

Additionally, different options regarding the vessel to be employed for the installation and maintenance activities of the Deep Green device were considered. These included either a specialised offshore vessel or any other ordinary vessel (e.g. fishing vessel). In the first case, the HAZID analysis is a prerequisite for the actual operation of the vessel and the operator of the vessel should comply with all statutory and Classification Society requirements. In the latter case, an ordinary vessel may consist of the usual marine crew (Captain, Engineer/s, Able and/or Ordinary seamen), which may not have the specific experience required in the offshore operations (e.g. heavy lifting, diving operations, etc.). In this case, a precise and detailed HAZID analysis was deemed necessary for the purposes of the installation, operation and maintenance activities at the overall Deep Green site including all potential hazards that could be developed in any particular circumstances.

Table 5: Part of the Hazard Identification process for the lifting operations of the offshore installation of the Deep Green device

Installation of device offshore			**Consequence index**				**Probability index**				**Risk index**					
Undesired event / Hazard	**Cause**	**Consequences**	**S**	**E**	**A**	**O**	**S**	**E**	**A**	**O**	**S**	**E**	**A**	**O**	**Risk control options/measures**	**Remarks**
Dropped/swinging equipment/device/tethers while installing, lowering/retrieving from water	Rigging failure	Injury/fatality, environmental damage, device/tethers/equipment damage/loss, operational time delay/loss	D	B	C	A	2	2	2	2	D2	B2	C2	A2	Certified rigging, inspection & maintenance of cranes	Environmental Management Plan (EMP), Safe Job Analysis (SJA) carried out where necessary
"	Crane overload	"	C	B	C	A	2	2	2	2	C2	B2	C2	A2	The crane is fitted with a load cell and cut-outs	"
"	Mechanical failure	"	C	B	C	A	2	2	2	2	C2	B2	C2	A2	Crane designed with appropriate dynamic factors for offshore operation	"
"	Untrained/inexperience crane personnel	"	C	B	C	A	2	2	2	2	C2	B2	C2	A2	Certified and experienced crane operators (specific training on ship cranes)	"
"	Wrong rigging practice (slings, hooks, shackles)	"	C	B	C	A	2	2	2	2	C2	B2	C2	A2	Correct positioning/rigging, SJA	"
"	Incorrect personnel positioning	"	C	B	C	A	2	2	2	2	C2	B2	C2	A2	Qualified marine/lifting operations crew, training	"
"	Poor communication	"	B	B	C	A	2	2	2	2	B2	B2	C2	A2	VHF radio communication between crane operator, deck crew, vessel bridge	"
"	Improper control of lifting operation	"	C	B	C	A	2	2	2	2	C2	B2	C2	A2	Qualified marine/lifting operations crew	"

Moreover, the results of the HAZID analysis were also verified and updated during a workshop carried out at the premises of the dpt of NAME at Strathclyde university in Glasgow with participants from all interested parties of the project consortium. Participants included the design company of the Deep Green device, a major classification society, the company involved in the installation activities of the device as well as a major consultancy company specialising in the renewables sector. All the above stakeholders contributed in a systematic review of the performed tasks and the comments originating from the review process were taken into account in the formulation of the revised version of the present study.

It should be also mentioned that various other hazards were identified at the initial HAZID stage such as e.g. rapture of oil & gas pipelines, subsea cables and impact to archaeological sites, ruins, shipwrecks, etc. Such areas of concern are not included in the current risk analysis study since these potentially hazardous areas are considered at the initial phase of the site selection of the Deep Green project (including the development of the Environmental Impact Assessment study) and they are dealt with in detail at that project stage.

4. HAZID ANALYSIS RESULTS

In this section of the present paper, the results of the HAZID analysis are shown. These include all the high-ranked identified hazards (Level 3 and Level 4) for each one of the activities of the Deep Green device mentioned (Installation, Operation and Maintenance) for all the different consequence categories i.e. personnel Safety (S), Environmental protection (E), Asset integrity (A) and device Operation (O). A small part of the above are shown in Table 6.

As discussed before, a full and detailed list of all the high-ranked hazards identified during the HAZID analysis for the offshore Installation, Operation and Maintenance of the device was created and is shown in [20]. In it, mitigation and/or prevention measures are also suggested in order to avoid the unwanted hazards for the mentioned activities.

Table 6: Part of the HAZID analysis results for the Deep Green device

			Risk index			
Examined area/topic	**Undesired event / Hazard**	**Cause**	**S**	**E**	**A**	**O**
1. Lifting operations	Dropped/swinging equipment/device/tethers while installing, lowering/retrieving from water	Rigging failure	D2			
	"	Poor communication	B4	B4	B4	
	"	Swinging due to vessel motions	C3		C3	
	Snagging	Excessive/unknown load weight	D2			
	"	High dynamic load during lifting operations	D2			
	"	Bad weather	D2		D2	
	"	Vessel motions	D2			
2. Seakeeping	Severe vessel movements	Severe sea conditions, vessel motion responses	D2			
3. Vessel stability	Stability loss	Cargo shifting		D2		
	"	Severe weather		D2		
4. Other vessel in the vicinity	Contact/collision	Watch-keeping error, not following procedures	D2			
	"	Mechanical failure propulsion, steering)	D2			
	"	Bad weather	D3			
	"	Poor communication	D2			
	"	High vessel density (e.g. fishing, leisure, working vessels)	D2			

In these terms, the following are the highest ranked hazards for all mentioned offshore activities:

• Occupational hazards: Exposure to hazards from entry into confined spaces (tanks, store rooms, etc.)

- Fire:
    - Fire in E/R & machinery spaces (switch gear, steering gear, ROV area, etc.)
    - Hot work leading to ignition of flammable substances
    - Bunkering leakage and ignition

For the examined area/topic of the Deep Green device complete/partial loss of operation, the following high hazardous areas are identified:

- Fire in the device (Faulty cabling, fuses, electrical failure)
- Grid power loss (Onshore power loss/causes)
- Catastrophic device failure for the wing, nacelle, tether, joints, swivel, foundation (Manufacturing fault, cracks, structural fatigue, fire, wing/nacelle flooding, tether joints collapse, waves axial forces on tether, etc..)
- Cables collapse (Cables overstressing, fatigue, manufacturing fault)
- Seabed collapse/erosion (Unstable soil/seabed condition)

Moreover, the overall results of the HAZID approach regarding the different areas of the offshore activities of the Deep Green are summarised below. These are distinguished in the high-ranked risks concerning the Deep Green itself as well as more generic areas of concern regarding the entire Deep Green project. The hazard list will be presented next in accordance with the risk consequence level to the overall operation of the project. Starting with the offshore installation of the device, the primary identified hazards are as follows:

for lifting operations

- Dropped/swinging equipment/device/tethers while installing, lowering/retrieving from water: certified rigging can be used together with inspection and maintenance routine of cranes
- Snagging of lifting equipment due to high dynamic or excessive static loading, bad weather or vessel motions: Lift plan and correct lifting procedures may be employed as well as crane operational limits monitored

for construction works (foundation, etc.)

- Dropped/swinging equipment/foundation while installing, lowering/retrieving from water: adequate procedures in place, competent personnel, secure rigging is a prerequisite in addition to Environmental Management Plan (EMP) and Safe Job Analysis (SJA) carried out where necessary
- Wrong installation of device: use of ROVs is suggested in this case together with following project installation plan in its full extent
- Entangled cables around foundation during installation procedure: specific installation procedure followed, ROV deployment when required

for the operations of ROVs

- ROV operations interfere with device/ vessel operations: good communication and supervision plan among team members
- Dropped/swinging ROV: adequate procedures in place should be used, competent personnel employed and secure rigging engaged

Floating device/equipment and the hazard of contact collision: potential damage to the device as the its size is small compared to vessel used for installation purposes

Regarding occupational hazards

- Personnel slips, trips and falls during installation offshore: safety working procedures should be in place, work risk assessment carried out as per offshore operations, harnesses used where needed, daily inspections carried out as well as good housekeeping onboard the vessel
- Man Over Board (MOB) incident: inspection and maintenance of equipment performed, adequate training of all personnel/crew involved in the operations and harnesses/life jackets used at all times

for health hazards

- Exposure to toxic gases from various chemicals used, etc.: crew/personnel training on chemicals use, PPE used, operational vents in place, inspection and maintenance of engines/equipment/sewage system

for general environmental hazards

- various types of pollution occurring from the vessel used and controlled by environmental management plans in place

in general for the vessel employed for the installation activities offshore

- Cargo shifting and severe weather encountered: proper sea-fastening used and management procedures in place addressed

Other vessel/s in the vicinity

- Contact/collision with other vessels: in this case a number of control options may include competent marine crew , proper watch keeping, inspection and maintenance procedures in place and DP capability among others

Regarding the Deep Green operation in the offshore environment, the high-risk areas identified and the risk control options/measures suggested are:

- Fire in the device: in this case, sensors should be used to detect any anomalies regarding voltage, temperature as well as fire-proof compartments and materials utilized
- Grid power loss: In this case, power redundancy (batteries used) will be needed while the generator may operate as a motor to drive the device in the 'parking' position
- Catastrophic device failure (wing, nacelle, tether, joints, swivel, foundation): For this hazard, a robust design should be a high priority as well as close monitoring, inspection and maintenance of the device and its operation performed
- Cables collapse: proper design, monitoring and inspection of cables followed by the technical details presented in the FMEA of the present study
- Seabed collapse/erosion: seismic and geophysical surveys should be conducted as well as scouring protection applied

In the field of the offshore maintenance of the device, particular attention should be attributed to:

- Lose track of device after surfacing: in this case reflective materials for the Deep Green could be used or other measures taken such as lights activated when surfacing as well as AIS transducer used in extreme cases
- Cables twisted/broken during maintenance operations: the device could be controlled to stay in 'parking' position or use cable cylinders near foundation to store slack cable
- Device tangled with tethers: in this case as well control options in place to enhance the controlling of the device, control system kicks-in on time
- Device not stabilised or maintaining 'parking' position: redundant control mechanism while device operational environment speed maintained at 1.5-1.7 m/sec
- Blades not stable/moving during retrieving device for maintenance: redundant control mechanism provided while maintenance is carried out during slack water
- Quick release mechanism malfunctioning/not working: robust design of quick release mechanism, inspection and monitoring at predefined intervals
- Bad weather conditions during maintenance operations: follow safety and operational procedures. In extreme cases, take additional safety measures
- Unexpected maintenance tasks occurring: floating balloon with radar reflectors for recovery of the device may be a risk control option

In terms of the diving operations, which might be needed in the case of installing and operating a device under scale in shallow waters, they are all classified as very hazardous as diving on its own is a high-risk activity. Particular attention should be given to:

- Hazards during routine diver deployment/retrieval
- Emergencies occurring while divers are in the water
- Undesired interaction between divers, device and ROVs

All the above-identified hazards are the higher ranked ones shown in the list of the overall HAZID analysis presented in this study. For more details, the reader is prompted to examine the detailed HAZID analysis included in [20].

5. CONCLUSIONS

This section discusses and provides insight into the conclusions and recommendations of the research presented in this study for one of the first stages of the innovative Deep Green project; that is the risk assessment for installation and service operations of the Seakite device. It also indicates the way for further research in this area. At this point, it is important to note that the study performed so far is the outcome of the initial design specifications and considerations regarding the overall operation of the innovative tidal power-converting device. The stage of the initial concept design is an iterative process, which necessitates re-thinking and re-working in order to finalise the details of the device and which, consequently will prove beneficial when re-visiting and updating the current study. Bearing the above in mind, the present study can be updated and expanded to include more details of the Deep Green device and the overall Deep Green project when the initial design will be further established and finalised. In these terms, the key elements of the work carried out and presented in this report are the following:

- Review of risk analysis and risk assessment methods and tools in the renewables, maritime and other industrial sectors
- Presentation of a risk analysis and decision making methodology to be followed for the Deep Green device and the overall Deep Green project
- Development of a thorough risk matrix to be used for the installation, operation and maintenance activities of the Deep Green
- Identification of the hazards in the installation, operation and maintenance activities of the device
- Identification of the high-ranked hazardous areas for the mentioned activities

In addition to the above, the research study conducted herein provides a rigid foundation for expanding into further research in the mentioned areas. Some of the recommendations that may enhance the proposed methodology are mentioned next:

- The overall Deep Green project activity areas/processes may further include the examination and risk assessment of the device transportation at sea (e.g. towing), and finally decommissioning and dismantling if applicable
- Regarding the hazard identification process, it may be expanded to include another consequence category and accordingly another risk category in terms of the reputation of the company involved
- Hazards and potential risks regarding diving operations have not been included in the present study (the use of divers will be avoided as much as possible while the use of ROVs will be preferred) but can be easily incorporated in the HAZID study
- Employ reliability tools such as Dynamic Fault Tree Analysis [21], [22]. The latter can be performed in either a qualitative or a quantitative way to examine the reliability and criticality aspects of the entire device as well as of its sub-systems and end-parts
- Include other system equipment such as array and export cables, transformer, grid connection, etc. if this is required
- Particular attention should be also drawn to various options regarding the employment of qualified and experienced sub-contractors for the installation and/or maintenance activities of the Deep Green device offshore.
- The Deep Green device may be also assessed according to the equipment that will be used i.e. innovative and/or existing equipment technology. In this respect, [23] provides a framework for carrying out this activity.
- Further studies can be performed in order to address the development of methods for handling of the full scale SeaKite during service and maintenance operation as well as its associated cost from the above-mentioned operations.

6. ACKNOWLEDGEMENTS

The work presented in this paper is part of the UK Carbon Trust funded project (Applied research Agreement 0913-091). The authors would like to express their gratitude to all the project partners who have provided their feedback on the initial results of this study.

7. REFERENCES

1. IEA. International Energy Agency, 2006.

2. GARRAD HASSAN & PARTNERS LTD. 'Study assessing the feasibility of adapting the Minesto equipment to low energy tidal streams', Deep Green project, 2007

3. HSE. 'Assessment principles for offshore Safety Case', *HSE publications*, London, 2006

4. HSE. 'Reducing risks, protecting people', *HSE publications*, London, 2002

5. NTS. 'Criticality analysis for maintenance purposes', Norsok standard Z-008, *Norwegian Technology Centre*, rev. 2, 2001

6. OREDA. 'Offshore Reliability Database handbook', 4th edition, *DNV*, Norway, 2002.

7. BS/ISO. 'Petroleum and natural gases industries-Offshore production installations-Guidelines on tools and techniques for hazard identification and risk assessment', *BS/ISO standard 17776*, Brussels, 2002

8. DNV. 'Marine risk assessment', Offshore technology report prepared for the UK HSE, London, 2001

9. SKJONG, R., VANEM, E. and ENDRESEN, O. 'Risk evaluation criteria', EU SAFEDOR project deliverable D.4.5.2, DNV, Hovik, Norway, 2005

10. IMO. 'Formal Safety Assessment (FSA): Consolidated text of the guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process', *MSC/Circ. 1023*, 2007

11. DNV. 'Risk management in marine and subsea operations', *RP-H101*, Hovik, Norway, 2003

11. ABS. 'Guide for risk evaluations for the classification of marine-related facilities', *Publication 117*, Houston, 2003

12. DNV. 'Guidelines on design and operation of wave energy converters: A guide to assessment and application of engineering standards and recommended practices for wave energy conversion devices', a study commissioned by the Carbon Trust, 2005

13. DNV. 'Certification of tidal and wave energy converters', *Offshore service specification DNV-OSS-312*, Hovik, Norway, 2008a

14. DNV. 'Classification based on performance criteria determined from risk assessment methodology', *Offshore service specification DNV-OSS 121*, Hovik, Norway, 2008b

15. THIES, P.R., FLINN, J. and SMITH, G.H. 'Is it a showstopper? Reliability assessment and criticality analysis for Wave Energy Converters', *Proceedings of the 8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009

16. SALCEDO, F., RUIZ-MINGUELA, P., RODRIGUEZ, R., RICCI, P. and SANTOS, M. 'OCEANTEC: sea trials of a quarter scale prototype',

Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 2009

17. CLARKE, J.A, CONNOR, G., GRANT, A.D., JOHNSTONE, C. and ORDONEZ-SANCHEZ, S. 'Contra-rotating marine current turbines: single point tethered floating system-stability and performance', *Proceedings of the 8th European Wave and Tidal Energy Conference*, Uppsala, Sweden, 2009

18. JONKMAN, S.N., VAN GELDER, P.H.A.J.M. and VRIJLING, J.K. 'An overview of quantitative risk measures for loss of life and economic damage, Journal of hazardous materials', vol. A99, pp. 1-30, 2003

19. LOER, K. and HAMANN, R. 'HazId for tanker operations', *EU SAFEDOR project deliverable D. 4.7.1*, GL, Hamburg, 2007

20. LAZAKIS, I., TURAN, O. and INCECIK, A. 'Risk assessment for installation and service operations', *Task 1.6, Project deliverable of the Deep Green project*, 2011.

21. LAZAKIS, I., TURAN, O., AKSU, SEREF and INCECIK, A. 'Increasing ship operational reliability through the implementation of a holistic maintenance management strategy'. *Journal of Ships and Offshore Structures*, Vol. 5: 4, pp. 337-357, doi: 10.1080/17445302.2010.480899, 2010

22. TURAN, O., LAZAKIS, I., JUDAH, S. and INCECIK, A. 'Investigating the reliability and criticality of the maintenance characteristics of a Diving Support Vessel', *Journal of Quality Reliability Engineering International*, doi: 10.1002/qre.1182, 2011

23. DNV. 'Certification of tidal and wave energy converters', O*ffshore service specification DNV-OSS-312*, 2008

8. AUTHORS' BIOGRAPHIES

Dr Iraklis Lazakis holds the current position of Lecturer at the dpt of NA-ME at the University of Strathclyde. He has several years of experience in the maritime industry in the areas of maintenance and repairs of ships. Among others, he has attended a number of surveys and dry-dockings of different ship types worldwide supervising the repair works carried out. He has also participated and contributed in industry, UK and EU funded research projects in the fields of operations and maintenance, reliability and risk analysis and assessment in the maritime and renewables sector.

Prof. Osman Turan is currently the Deputy Head of department at the dpt of NA-ME at the University of Strathclyde. He is one of leading experts on safety, design for safety covering, human factors, decision support system, and advanced design and optimisation techniques using artificial intelligence. He has been involved forefront of the waterborne safety and contributed significantly to the development of safety related rules at various platforms including IMO. He has been involved in many maritime accident investigations using pioneering techniques to establish the reasons of the accidents including human factors and develop solutions to eliminate/mitigate the accidents and safety critical conditions. Prof. Turan has been involved in several European Research programmes as a principal investigator as well.

Ted Rosendahl, is currently working with Offshore Operations at Minesto, where he during the first years of development was responsible for the technical department and it's organisation with the overall responsibility for the research and development activities. He has over thirty year of experience in the offshore and marine industry. He has wide international experience in product development and project management within the areas of production, mechanical engineering, hydrodynamic design, model testing, full scale testing.