Current & Tidal Energy Converters Farm Levelized Cost of Energy Optimisation Based on Reliability Assessment

Nicolas LARIVIERE-GILLET, Marine Renewable Energy Engineer at BUREAU VERITAS MARINE & OFFSHORE

Loic KLEIN, Risk & Reliability Engineer at BUREAU VERITAS MARINE & OFFSHORE

Raoul CABON, RAMS Department Manager at NAVAL ENERGIES

Gautier MAIGRET, R&D Engineer at NAVAL ENERGIES

Théo LARAIGNOU, R&D engineer at NAVAL ENERGIES

ABSTRACT

With more and more Current & Tidal Energy Converter (CTEC) technologies and worldwide opportunities to develop pilot or commercial projects, the renewable energy industry is now moving forward to achieve cost competitive development. Even if the current electricity price is shown as a bottleneck impacting viability of new commercial projects, CTEC projects remain a priority for many countries as currents and tides are seen as predictable sources of energy. As very limited feedback is currently available, the industry is now looking towards the first projects to be on stream to validate economic models initially based on unstable assumptions. This paper aims at demonstrating how reliability techniques such as Reliability, Availability & Maintainability (RAM) assessment can allow overall CTEC supply chain to adjust their economic model, to reach a lower Levelized Cost of Energy (LCOE) and design reliable and safe CTEC farm architectures. By using straight from concept stage an adapted RAM tool coupled with an efficient RAM assessment, it will be possible to ensure design has been conducted effectively with respect to production performance as well as optimized maintenance & repair strategy. Later on, by incorporating on a regular basis operational data coming from industry return of experience, companies will be able to capitalize on it for future projects.

The paper will first give an overview of the CTEC market outlining the main challenges. Then, based on recent projects the authors have been involved with, it will detail the reliability methodology applied to ensure the profitability of such innovative developments. This second section will focus on the key parameters and assumptions to be considered in order to assess production availability of the full CTEC architecture and then LCOE in the most appropriate manner. Finally, after having pointed out the ins and outs of RAM analyses, a case study will be developed to illustrate and quantify the benefits of the proposed approach.

INTRODUCTION

RAM analysis is a modelling technique that has its origin in the military sector involving the V-1 missile team during World War II (MIL-HDBK-338B, 1998). It was here that it became first understood that an improvement in the reliability of individual components and reconfiguring the system to improve reliability resulted in an increased likelihood of success. Reliability was then quickly adopted in industries where understanding of an improvements in the reliability of complex systems was required, namely by the National Aeronautics and Space Administration (NASA), the nuclear power industry and Oil and Gas industry to prevent such accidents as experienced at a nuclear power plant at Three Mile Island (USA, March 28, 1979), the explosion of the space shuttle Challenger (USA, January 28, 1986) or even the Piper Alpha offshore platform explosion (Scotland, July 6th, 1988).

Facing major economic challenges, CTEC industry has embraced the idea of reliability analysis for driving design improvements and increasing electricity production availability. Reliability, Availability & Maintainability analysis provides a perfect tool allowing designers to assess complex systems performance in a rapid and cost effective manner before costly construction or modification is implemented.

CTEC energy sector is currently emerging from a research phase involving tank testing or temporary deployment at sea of single devices towards pre-commercial deployments involving a larger number of machines interconnected. Based on this natural evolution related to new technologies development, it is anticipated that CTEC industry will have to focus on two major challenges:

- demonstrating high reliability and cost efficient maintainability of the machine itself; and
- optimizing from the early stages of development overall farm architecture as well as related maintenance and sparing strategy.

By overpassing these two bottlenecks for the industry, significant progress in the CTEC project bankability can be achieved.

After having introduced an overview of the CTEC market as well as the basis of RAM assessment, the paper will demonstrate through a case study inspired by the Raz Blanchard pilot farm developed by EDF Energies Nouvelles together with Naval Energies how RAM assessment can impact positively project economics.

CURRENT & TIDAL TECHNOLOGY MARKET OVERVIEW

Current & Tidal Energy Converter Technologies

The Current and / or Tidal Energy Converters are electricity production units using current or tidal energy. Various designs and shapes exist today but the current paper will focus on the technologies composed of the main components as described herebelow and illustrated in Figure 1:

- *The rotor*, composed of blades with or without duct (also known as “shroud” or “venturi”) and central hub or central/external bearing (for open-centre turbines);
- *The nacelle*, structural part enclosing mechanical and electrical components such as generator, converter, brake, gearbox (optional) etc.; and
- *The support structure*, including substructure and its foundations.

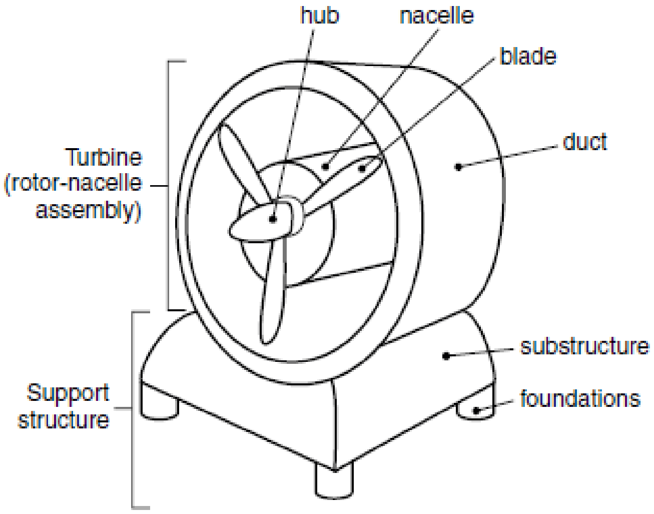

Figure 1 - Components of a Current and Tidal Energy Converter

Tidal Energy Business

At the time of this paper, CTEC business is mainly considered as a niche market with limited potential locations over the globe. Based on the technologies developed today, it seems that economically viable site for Tidal farms developments are located where the current velocity is over 2 m/s. Most of the locations considered today for TEC developments are located close to the coastal area. Figure 2 presents an example of potential commercial TEC development in France based on current speed expressed in knots.

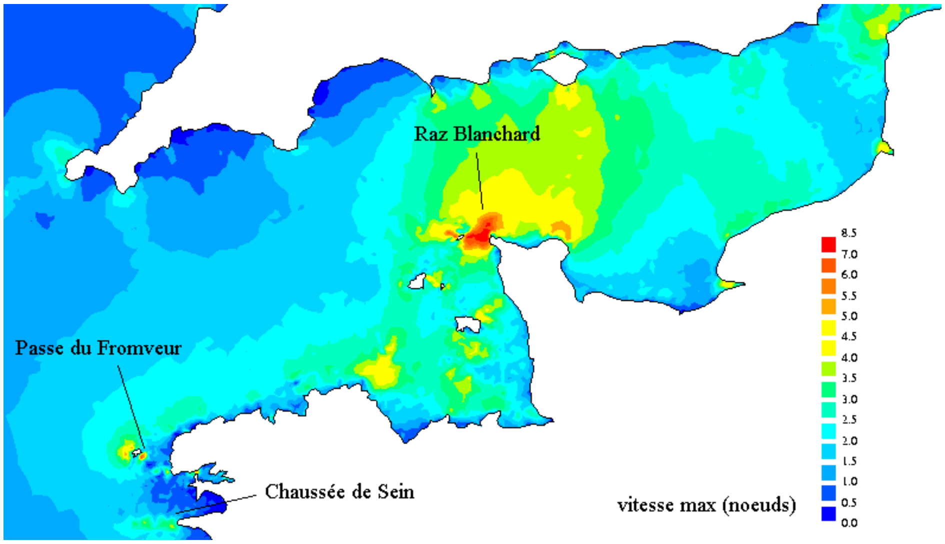

Figure 2 - North of France and South of England tidal energy potential (source: Newsidenergy, 2011)

While there is no efficient way today to store electrical production, CTEC developments appear as a major asset for Renewable Energies production as most of the humans over the globe are located close to a coastal area and tides or currents are phenomenon highly predictable that will allow future commercial development to provide electrical grid or local inhabitants with a plannificable source of energy. However, main constraints on the CTEC industry is related to the high Levelized Cost Of Energy making CTEC commercial development difficultly economically viable even with interesting feeding tariff or encouraging governmental policies. Thus, some of the key elements for a successful development of the CTEC industry are:

- Increase CTEC reliability to increase electrical production availability;
- Reduce Capital Expenditure of individual components / machines as well as overall farm development (i.e. reduced number of components, adapted level of redundancy, optimize layout…etc);
- Decrease in maintenance & logistics costs mainly related to offshore vessel intervention to reduce Operating Expenditures;
- Possibility to carry out offshore intervention over a larger metocean window to reduce period of unavailability;
- Strengthen regulatory context to standardize technologies development and farm development in order to reassure project developers, investors, bankers and insurers; and
- Develop long term and adapted environmental and financial policies to ensure economic stability of CTEC developments (i.e. not as it is with volatile oil price for instance).

The following sections will provide element of answers for the 3 first challenges mentioned hereabove.

IMPROVING LCOE BY USING RELIABILITY TECHNIQUES

Value of Reliability, Availability & Maintainability (RAM) Modelling

One of the most important parameter to quantify, when a technology or project developer wants to optimize the Return of Investment of an asset, is the production availability. Thus, carrying out a RAM analysis to better understand the production availability and the constraints on maintainability during the different phases of the project is then a powerful approach that will provide with important inputs to the decision making process. The RAM analysis will allow understanding of the reliability based interactions within the facilities and will provide the different design teams with a tool for quantifying system performance, identifying the critical aspects of the design and allow the impact of varying design, operations and maintenance criteria to be understood. It will ensure the system design is reliable and that production availability will not be impacted by specific bottleneck.

The ideal timing for a RAM analysis is immediately following early design phase. RAM modeling can then be updated at each phase of the project to ensure the recommendation of the study have been implemented and that other modifications performed during detailed phases will not impact negatively the project. General ideas to achieve an increase in availability are presented in Figure 3:

Figure 3- Reliability, Availability and Maintainability

Where (-) indicates constant, (↑) indicates an increase and (↓) indicates a decrease.

Some of the benefits of the RAM analysis are:

- Quantification of production availability on a time varying basis to predict performance over the entire life of the development;
- Identification of critical production loss events due to simulated failures of components;
- Recommendations for design changes;
- Guidance for future OPEX allocations in the form of the frequency and duration of unplanned maintenance requirements;
- Quantification of the impact of operations and maintenance philosophies.

RAM Key Definitions & Principles

A short description of the definitions and terms applied to RAM analysis is necessary before detailing it in the next parts.

Failure and Failure Mode

A failure can be defined as the non-conformance to some defined performance criterion, where as a failure mode can be defined as the effect by which a failure is observed on the failed item [5].

Reliability

Reliability is the ability of an item to perform a required function under given conditions for a given time interval [6]. Reliability can be thought as the probability of conformance to a specific function over a specific time. Reliability is most commonly defined in association with the Mean Time between Failures (MTBF), this concept will be further discussed in the subsection Availability.

Maintainability

Maintainability is the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can be perform a required function, when maintenance is performed under given conditions and using stated procedures and resources [6]. Maintainability can be thought as the typical time spent fixing a problem, allowing it to get back into service. Maintainability is most commonly defined in association with the Mean Time to Repair (MTTR).

Availability

Availability is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided [8]. There exist a number of availability classifications. Production availability is the ratio of production to planned production (e.g. commonly featured by simulating models using Monte Carlo). Inherent Availability considers only the corrective maintenance downtime of a system. Operational Availability is a measure of the average availability over a period of time including all sources of downtime (i.e. logistics, mobilization, etc.).

For a repairable system, commonly used to model systems, the inherent availability can be expressed by:

$$A = \frac{MTBF}{MTBF+MTTR} \qquad (1)$$

where, $MTBF = Mean\,Time\,to\,Failure\,(MTTF) + MTTR$. However, normally the MTTF is much greater than MTTR and thus MTBF ≈ MTTF

Production Availability

Production Availability is a measure of the actual performance of a production system accounting for production loss due to planned and unplanned outages against the potential production of the system given no outages have occurred within a given system life.

Thus production Availability can be expressed as the percentage:

$$P = \frac{Actual\ production\ allowing\ for\ Planned\ and\ unplanned\ donwtime}{Potential\ production\ with\ no\ downtime} \times 100 \qquad (2)$$

Bath Tub Curve

The failure rate λ(t) is a function that describes the number of failures that can be expected to take place over a given period of time. To describe the failure rate the bath tub curve (see Figure 4) [8] is used commonlyin reliability engineering. The failures exhibited in the first part of the curve, representing a constant failure rate, relates to failures that occur randomly during the normal life of the component. The final section, representing an increasing failure rate, is termed wearout failures as increased failures occur towards the end of the components useful life.

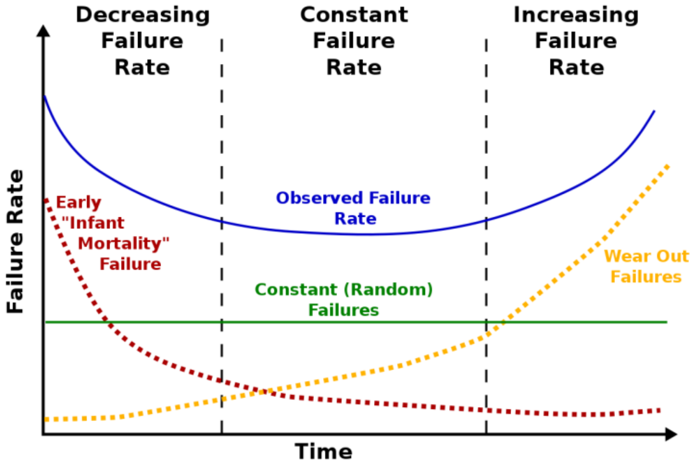

Figure 4 - Bath Tub Curve

Depending on the failure data available, RAM analysis can assume a variety of distributions to describe the system most accurately. Commonly a constant component failure rate is assumed when maintenance and operations records are not available [5]. Reliability can then be represented by:

$$R = e^{-\lambda t} \qquad (3)$$

where, R is the reliability, λ is the failure rate and t represents time.

Criticality

Systems and equipment are categorized as either ‘critical’ or ‘non-critical’ in terms of their impact on production. Failure of critical equipment results in the loss of normal production associated with that item. Conversely, failure of non-critical equipment has no impact on production. For instance, a parallel configuration can be described with a term such as “2 x 100%”. 2 x 100% critical units do not cause production losses unless both items have failed and are ailed simultaneously (i.e. redundancy [9]). Conversely, failure of either one of 2 x 80% critical units will cause normal production to reduce to 80%.

Monte Carlo simulation

There exists a number of numerical methods used in the field of prediction to build simulation models (e.g. Markov, Petri Net, etc.), but the Monte Carlo modeling technique is the most widely used for the simulation of complex and dynamic interactions [1]. A random number generator is used to provide a probability of a failure occurring which in turn is used to calculate the time to the next failure. The Monte Carlo model can be used to model any failure pattern or repair characteristic for which data is available. The outputs are a time-based availability curve for the length of the simulation.

RAM Modeling Exercise

RAM analysis methodology is structured in 6 main steps as detailed in Table 1:

- Information gathering and project familiarization,
- Development of Reliability Set of Data,
- Assumptions development and validation,
- Model construction and simulation,
- Result Generation, and
- Recommendations and sensitivity cases.

Table 1 - RAM Modeling Methodology

STEPS	INFORMATION / DESCRIPTION
1.Information gathering and project familiarization	▪ Equipment list ▪ System decomposition ▪ Understanding of failure modes ▪ Historical and estimated failure rates ▪ Logistic times (understanding of crew staffing, spare parts holding, etc.) ▪ Failure impact on production, capacity and safety ▪ Understanding of any third party requests for shutdown
2.Development of reliability data set	▪ Historical operating records ▪ Reliability data ▪ Equipment vendors data ▪ Engineering judgment
3.Assumptions	▪ Identification of equipment critical to production ▪ Development of Reliability Block Diagrams (RBDs) (understanding of equipment redundancy and configuration) ▪ Operations and Maintenance Philosophy ▪ Identification of sensitivity analysis
4.Model construction and simulation	▪ Build RAM model ▪ Perform simulation with various model inputs ▪ QA/QC check of the model
5.Results generating	▪ Quantify performance of the system in terms of overall availability ▪ Presentation of P_{10}, P_{50} and P_{90} probabilities of exceedance for understanding confidence levels ▪ Annual / Seasonal availability distribution ▪ Average duration spent delivering different production outputs ▪ System criticalities ▪ Main contributors to downtime
6.Recommandations	▪ Understanding of bottlenecks and changes in equipment configuration ▪ Maintenance scheme optimization ▪ Understanding of spare holding and lead times to source spares optimized against availability targets and the total costs of holding spares ▪ Maintainability and operability sensitivity cases

RAM Tools used for case study

Optimise©, a software developed by Bureau Veritas

Bureau Veritas has developed its own software suite Optimise© to undertake RAM and supply chain analysis for about 20 years. It is based on Monte Carlo simulation. Optimise© is compliant with ISO 20815 production performance analysis requirements.

Optimise© is combining:

- Detailed RAM capabilities of traditional RAM software, including planned and unplanned downtime, operations and maintenance philosophies, production and demand profiles;
- Support tool for import of Library Elements from an external file based on Reliability Register;
- Shipping simulation capabilities of sophisticated ‘tank to tank’ shipping tools, including fleet configuration, weather and mechanical delays, tidal and night berthing restrictions, and a host of other aspects necessary for realistic shipping simulation; and
- Rapid Model Building and Editing enhancements to the user interface.

Naval Energies RAM Tool

Naval Energies has been developing internal software tools for more than three years. The purpose of the approach was to achieve a global modelization and optimization of a tidal farm through several specific software, each one dealing with one specific aspect of the farm.

In this context, the RAM analysis was identified as one of the key topics when it comes to designing a tidal farm and optimizing its performance. Therefore a dedicated methodology has been developed and implemented in internal software.

Based on Monte Carlo method, the model takes into account reliability data, O&M strategies (corrective, predictive or preventive maintenance for instance) and accessibility assumptions to simulate a great number of lifecycles of the tidal farm. The user can then extract the main data (availability, number of maintenance operations, production…) and compare different designs of the farm.

CASE STUDY: TEC FARM LCOE OPTIMISATION BASED ON RELIABILITY ASSESSMENT

Project Description & Objectives

This case study aims at assessing production availability of a TEC farm similar to the development planned for “le Raz Blanchard” and located in France. The current case study will consider five (5) TEC connected together in a daisy chain arrangement as per Figure 5.

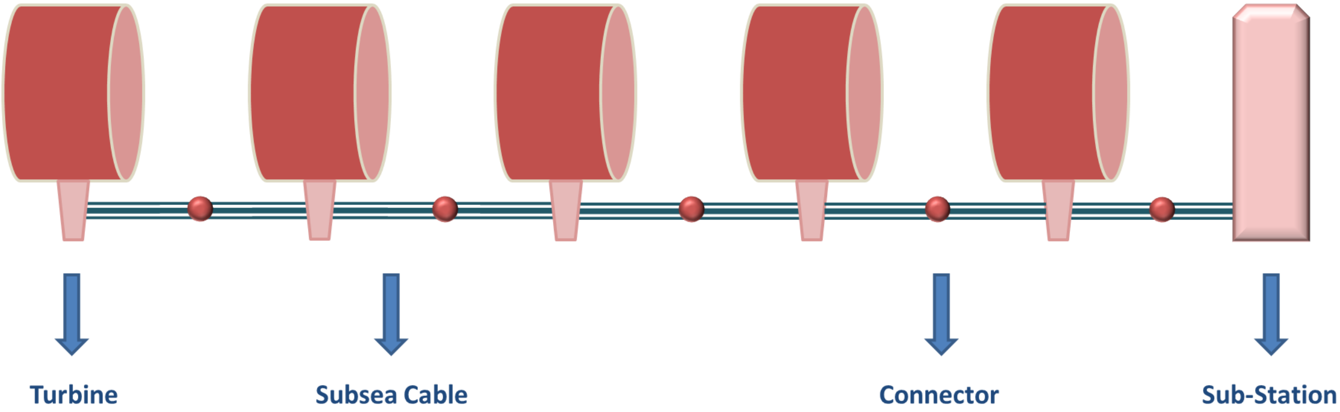

Figure 5 – Base Case of Tidal Farm Development Overview

The pre-commercial farm will include:

- 1 sub-station;
- 5 turbines;
- 5 subsea connectors; and
- 10 cables.

Main objective of this case study is to demonstrate how RAM analysis can be used to assess production availability of a TEC farm architecture in order to ensure electricity production target is achieved. Based on case study conclusion, it will be possible to define a series of sensitivity cases that could be used at a later stage, together with CAPEX evaluation, as a basis of the evaluation dossier used for the Final Investment Decision.

Main purpose of the RAM analysis is to:

- evaluate the availability of the TEC Farm development in terms of electricity produced;
- identify and rank the critical systems and components contributing to production losses;
- provide a baseline set of results for use in further sensitivity analysis; and
- identify reliability issues in the designs to recommend changes.

Reliability Data

The single most important issue in the RAM process is the data used to describe the unplanned failure and subsequent repair of equipment. It is fundamental that the data is appropriate and that the project team has confidence in it. Without such confidence the benefits that could be realised from the study will be limited. It is especially true when RAM assessment is carried out on novel technologies or with technologies with very little return of experience as operational reliability data are rarely available.

A specific workshop session was held between Naval Energies operational personnel and Bureau Veritas RAM specialists in order to obtain the most appropriate reliability data to be applied to the case study.

Most of the reliability data selected has been adapted from existing installations / components used in different environments or has been defined based on the availability target defined by the project (i.e. reverse engineering). For confidentiality reasons, data have been simplified and modified within the proposed case study but importance will be given to the interpretation of the results.

The model will systematically incorporate exponential distributions to represent the failure rate of equipment. The use of exponential distribution assumes the failure rate function is constant and independent of time, in which case the failure rates are assumed to be exponential distributed with λ parameter. It will then be considered that the equipment will not last until the end of its useful life but that a random failure will occur.

Exponential Distribution has been used to represent the Repair duration. It is expected that the repair data is an average data and can include extensively long repair time as well as short repair. Exponential distribution will be then able to cover all types of repairs around an average value.

Asset Register, summarizing reliability data for the case study, is presented in Table 2.

Table 2- Asset Register

TEC Components	**Reliability Data selected for the project (Critical Failure Mode only)**		
Compontent Type	**MTTF (years)**	**MTTR (h)**	**Preparation Time**
Hub	**40.00**	**48.00**	**3hrs** Connection / Disconnection and lifting / laydown
Nacelle	**5.00**	**48.00**	**3hrs** Connection / Disconnection and lifting / laydown
Rotor	**10.00**	**48.00**	**3hrs** Connection / Disconnection and lifting / laydown
Blades	**5.00**	**48.00**	**3hrs** Connection / Disconnection and lifting / laydown
Duct	**40.00**	**48.00**	**3hrs** Connection / Disconnection and lifting / laydown
Substructure	**50.00**	**48.00**	**3hrs** Connection / Disconnection and lifting / laydown
Foundation	**100.00**	**-**	-
Subsea cable	**10.00**	**0.00**	**3hrs** Connection / Disconnection and lifting / laydown
Subsea connector	**10.00**	**8.00**	**2hrs** Connection / Disconnection and lifting / laydown
Substation	**20.00**	**12.00**	**2hrs** including total shutdown time, scafolding, restart

Preparation time including permitting process, connection/disconnection of subsea connector and other are not taken into account in the MTTR and are presented separately in the Asset Register (Table 2).

Mobilisation time is as well excluded from MTTR. A triangular distribution with (min 1 week, peak 2 weeks, max 1 month) will model mobilisation time that includes the time to mobilise the crew, the spare components (if necessary) and the intervention vessel on site and come back to port as well as reverse operation to bring back the repaired component. Indeed, it is intended that most of the repairs will necessitate the time to bring the failed equipment from site to port, wait for its repair and bring it back at sea.

Main Assumptions

RAM model describes equipment in terms of their capacity, redundancy, and failure effect. The capacities, redundancies and failure effects used in a specific RAM model are collectively referred to as the model assumptions. To describe RAM models, key assumptions to be documented are Reliability Block Diagrams, an Asset Register (see Table 2) as well as the list of critical equipment of each system.

Thus, the case study will consider a 20 year operating Tidal Energy Converters Farm. Each of the five TEC can produce 2 MW peak. Average production per year for overall farm is estimated at 43800 MWh without considering any unplanned failure.

Other key assumptions are:

- Blades are assumed to induce a 20% loss of production when failed;
- Failed subsea cables will be replaced directly while subsea connectors are assumed to be repairable;
- Only one Intervention Vessel is available for the whole farm;
- Spare components (subsea cables for instance) are assumed readily available;
- Foundations are not reparable and full turbine will be replaced after one year at a new location; and
- Foundation failure will prevent turbine from producing but not from transferring electricity.

Results

In order to establish average results and confidence levels, the RAM model was run for 1,000 individual lifecycles considering 20 years as the system life. Simulation has been carried out using both RAM software in order to ensure consistency and convergence of the results. Considering an availability of 100%, the Base Case was simulated for a maximum electricity production rate of 876 000 MWh (i.e. 43 800 MWh per year over 20 years). Summary results are presented in Table 3.

Table 3 - Results Summary

Performance Measure	Mean Average Value
Average Production Availability (%)	**90.24**
Average Production (MWh)	**790 510**
Total Average Downtime (days/year)*	**32.78**

(*) Total Average Downtime takes into account only unscheduled downtimes

Figure 6 presents the variation in average annual availability over the life of the project. Each of the annual availabilities represents the average availability over 1,000 lifecycles for each year.

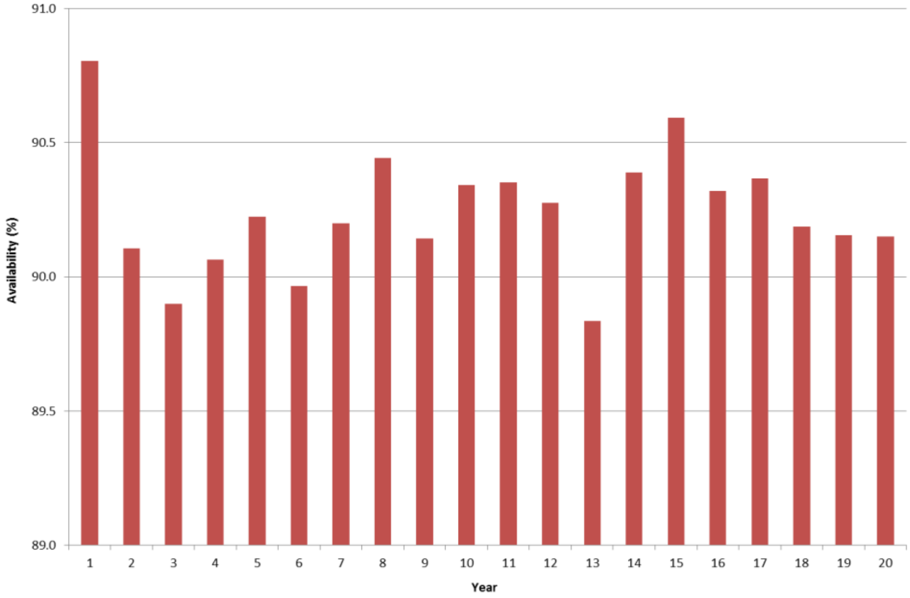

Figure 6- Annual Availabilities

Key points to note from Figure 6 are:

- The average availability over the 20 year system life is 90.24%.
- Variation around the average value is very low (about +/- 0.5%) meaning contributors to downtime are impacting production in a stable and repetitive manner.
- First year is particularly high in availability as most of the MTTF are high (i.e. > 5 years).
- Mobilisation time varies from 1 week to 1 month and is then one of the main responsible for the unavailability repartition.

Figure 7 presents the distribution of average system availability for the over the 20 year system life.

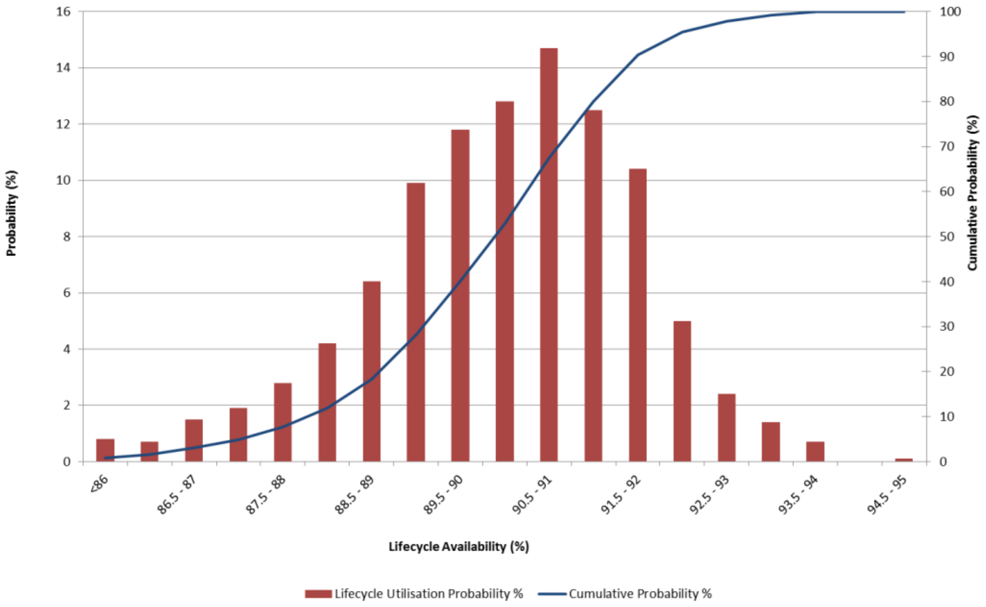

Figure 7 - Production Availability Distribution

Key points to note from Figure 7 are:

- The P10 is 88.22% (which means there are 90% of the values over 88.22%) and the P90 is 91.97% (which means there are.10% of the values over 91.97%).
- There is a low but non-zero probability of experiencing system availability lower than 86%. This low availability is due to the combination of simultaneous failures in different turbines as well as relatively long mobilization time. Failures of turbine 4 and 5 are particularly critical as well as they bring the production below 50% due to their location in the daisy chain.

Criticality analysis identifies the systems, equipment items or events that contribute the most to overall production losses, thus enabling a project team to focus on the areas of a design that will give the biggest improvements.

Figure 8 presents a breakdown of losses by system. As Tidal Turbine 5 is the last element of the production chain it is then logical to identify the corresponding system as the main contributor to downtime with about 32% of the overall production loss. Each turbine contributes then proportionally to its position / ranking within the chain of element.

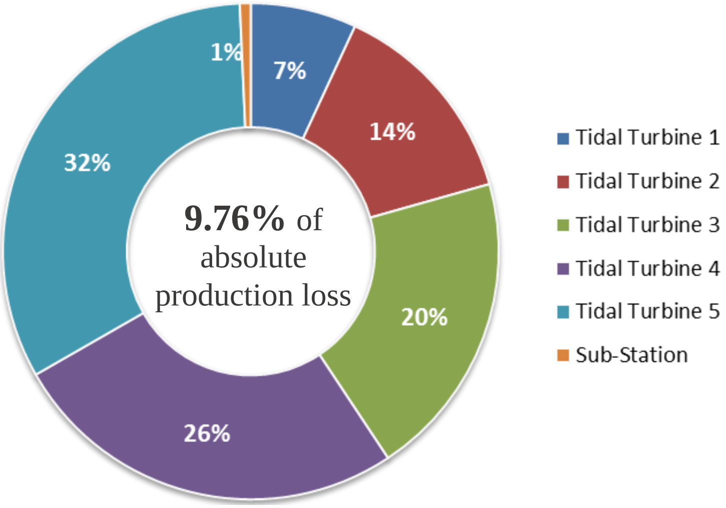

Figure 8 - Systems Criticality Chart

Figure 9 presents the subsystem breakdown for the tidal turbine 5, which is the main contributor to the overall Tidal Farm downtime. The results are presented as losses relative to the tidal turbine 5.

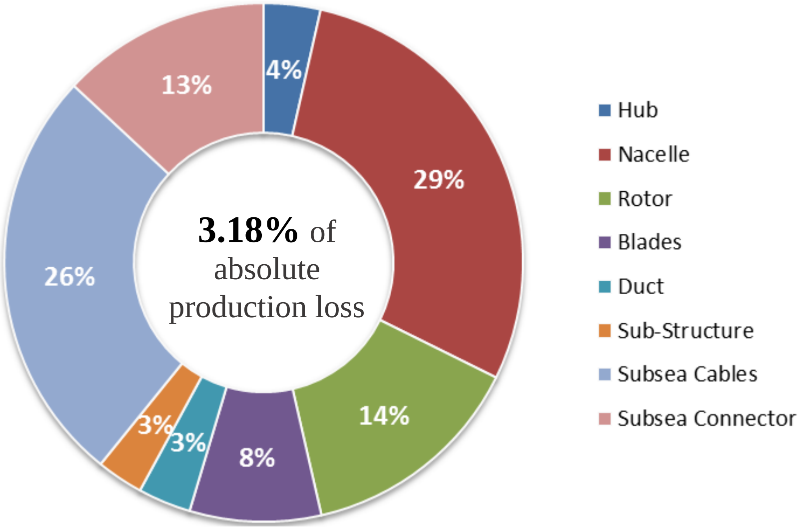

Figure 9 – Equipment Criticality for Tidal Turbine 5

Based on reliability data selected for the project, Figure 9 identifies the nacelle as well as the subsea cables as the two main contributors to downtime within the tidal turbine design. Even if the cable has been considered as replaced without being repair, the relatively low MTTF as well as the fact that each turbine will be connected to 2 cables, bring the subsea cables as a major contributor to downtime.

Even if very unlikely, failure of sub-structure can contribute up to 3% to tidal turbine losses because of the 1 year replacement time by a new turbine. During this year, turbine will be able to transfer electricity but will not produce the 20% required to reach the maximum production.

Sensitivity Case

Because of the very low level of redundancy within the system, it appeared that one interesting sensitivity case to be developed will be the case of the “loop”. Loop will consider an additional pair of subsea cable and one connector to be linked directly from tidal turbine 1 to the sub-station. Figure 10illustrates the new configuration to be tests.

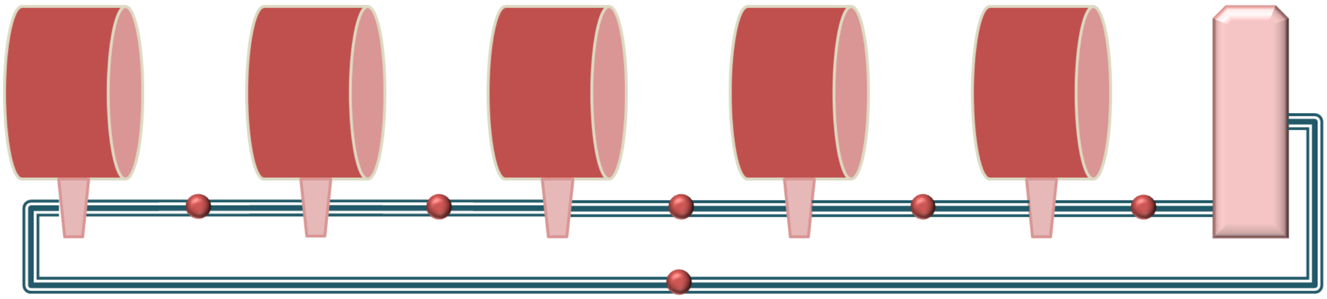

Figure 10 - Sensitivity Case of Tidal Farm Development Overview

Main interest of this configuration will be the possibility to avoid the “loss” of a turbine preceding the failed turbine (i.e. in the case of the daisy chain, when turbine 3 fails, turbine 1 and 2 cannot transfer the electricity they produce and production is then reduced to 40% because of the 3 turbines out of 5 configuration).

Conclusion of the Case Study

The case study developed has been used to test various reliability dataset as well as different configurations (even if only the daisy chain has been presented in this paper) in order to achieve targeted electricity production output. As reliability data remain the main concern for such analysis, it appears that success in conducting RAM analysis is directly link to the capability of running a large number of scenarios in order to prepare adaptable development where reliability issues could be balanced by a cost effective maintenance strategy. While the 90% overall availability found in the case study can still be discussed versus the level of details involved as well as the reliability data used for the model, RAM study fix the first basis to target reliability performance for each of the individual component that will impact the project. RAM analysis performed on the current case study has also identified some unlikely scenarios that could induce considerable loss of production if not balanced by a proper maintenance strategy (ex: loss of the sub-structure).

CONCLUSION

The production availability is one of the most important parameter to ensure a proper Return of Investment of a Marine Renewable Energy farm. Once the production capacity and the production availability target are set up, a reliability assessment needs to be carrying out in order to ensure that the process is designed to reach, as a minimum, this availability target. In many high tech industries such as aeronautics, automotive or oil & gas, RAM Analysis is often considered as one of the most powerful assessment tool to validate the project economics.

Compared to other energy related industries such as the Oil & Gas industry, Marine Renewable Energy devices have additional constraints related to:

- The lack of reliability data (no existing database, such as OREDA for Oil & Gas sector)
- Very high dependency of environmental site conditions (current, swell, …)
- Technical difficulties for Operation & Maintenance (no ROV or divers possible in high current areas)
- Economic difficulties for Operation & Maintenance (Vessel mobilization price very high compare to price of the energy produced)

These constraints induce today an unacceptable LCOE that can be only balanced if properly considered at the earliest stage of development. RAM becomes even the most important tool to solve the trade off between CAPEX and OPEX that is often far from non mature industries preoccupations.

Even if very powerful and cost efficient, the value of RAM is constrained by the lack of available reliability data for such new installation and by the ability to think ‘outside of the box’ to develop worthwhile and value adding ‘what-if scenarios’. It has been found that it is of the utmost important to define clearly all the assumptions to be taken into account and invest as much time as possible in sensitivity cases to assess the different options but also to valid successfully the design phases, not only with the good design, but with the best one.

REFERENCES

[1] MIL-HDBK-338B, “Reliability Prediction of Electronic Equipment”, Department of Defense, 1998
[2] ReliaWind report summary, European Commission, http://cordis.europa.eu/result/rcn/55560_fr.html
[3] Economic and Reliability Assessment of a Combined Marine Renewable Energy Platform, Fiona Devoy McAuliffe, Laura-Mae Macadré, Martin Heyman Donovan, Jimmy Murphy, Katie Lynch
[4] Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters, Anthony Gray, Beth Dickens, Tom Bruce, Ian Ashton, Lars Johanning
[5] Reliability, Maintainability and Risk, Butterworth-Heinemann, Smith D., 1997
[6] International Electronichal Vocabulary (IEV) Online Database, IEV, http://www.electropedia.org/iev/iev.nsf/welcome?openform
[7] Reliability mathematics: Fundamentals, Practices, Procedures, Amstadter B.L., 1977
[8] Fundamentals of Electronic Systems Desing, J. Lienig, H. Bruemmer, 2017
[9] Reliability in Engineering Design, Lamberson L.R. and Kapur K.C., 1977
[10] RAM Study Guideline, H. Lawrenz, Bureau Veritas, Perth, Australia, 2014
[11] Regularity Management & Reliability Technology”, NORSOK Z-016, Rev 1, December 1998, section 6.2 Qualification and application of reliability data, page 22.
[12] Offshore Reliability Data Handbook (OREDA), SINTEF Industrial Management, 5th Ed, 2009