Reliability and Cost Assessment of Critical Components: Electrical generator failure of IDOM wave energy converter

Julia Fernandez-Chozas, Patxi Etxaniz, Pablo Ruiz-Minguela, Pär Johannesson and Joao Cruz

Abstract— **Wave energy technologies must overcome several challenges related to cost, performance and reliability to unleash their full potential. This paper focuses on a selected critical component representative of Oscillating Water Column devices, namely the electric generator; and the assessment is based on the MARMOK wave energy converter.**

VALID is a 3-year Horizon2020 funded research project. Through VALID, IDOM – the developer of MARMOK - aims at increasing the overall energy conversion by using generators with reduced nominal power that operate at higher peaks with respect to nominal.

The present study relates the reliability of the critical component (the generator), its efficiency and the ratio between maximum power and nominal power to a performance and cost analysis of the Wave Energy Converter (WEC). A balance should exist between MARMOK's capital expenditures, energy yield and generators' required maintenance.

A model is presented in the paper, which will be made publicly available once validated in the three user cases of VALID. This is the first publication of the model and process. Preliminary results are promising, indicating there is an optimal generator sizing that has the potential of minimizing the cost of energy of MARMOK by half.

This work is part of the Verification through Accelerated testing Leading to Improved wave energy Designs (VALID) project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

J. Fernandez-Chozas is with Julia F. Chozas, Consulting Engineer, Frederiksborggade 1, 1360 Copenhagen, Denmark (e-mail: info@juliafchozas.com).

P. Etxaniz is with Idom Consulting, Engineering, Architecture SAU, Avenida Zarandoa, 23, 48015 Bilbao, Spain (e-mail: petxaniz@idom.com).

Pablo Ruiz-Minguela is with TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, E-48160 Derio, Bizkaia, Spain (e-mail: jpablo.ruiz-minguela@tecnalia.com).

Pär Johannesson is with RISE, Brinellgatan 4, 501 15, Boras, Sweden (e-mail: par.johannesson@ri.se).

Joao Cruz is with Yavin Four Consultants, Rua Frei Carlos, Lote 7, 2 Esq, 7000737, Evora, Portugal (e-mail: joao.cruz@yavinfourconsultants.com).

Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-516

Keywords— **electric generator, failures, hybrid testing, LCOE, operations and maintenance O&M, power take-off PTO, reliability, VALID.**

I. Introduction

It is believed that current testing procedures in the wave energy sector are not well-balanced. As learned from several European-funded projects such as [1], [2], [3] and [4], there is a lack of evaluation of future system performance at early stages of technology development. In fact, most laboratory testing at early development stages has been focused on functional tests (proof of concept and power performance assessment, for example) disregarding other key performance measures such as reliability and survivability. A new testing procedure that aims to reduce development time and cost, while enabling better understanding of reliability and survivability of critical components at early Technology Readiness Levels (TRLs) is been proposed within the VALID research project [5].

VALID is a Horizon 2020 research project where fourteen partners around Europe are collaborating into developing a new hybrid testing platform and methodology for critical components. VALID aims at integrating both reliability and testing methods together with relevant data on component failures early in the design and testing process to ensure that the proposed testing procedure is built upon past experience.

The project will validate the new hybrid test platform and methodology through three user cases, which have proved to be critical for long-term survivability and reliability of structures and power take-off systems and represent existing challenges for the wave energy sector.

In the context of VALID, the work in this paper relates reliability of the critical component to the performance and cost of the whole system, i.e. the wave energy converter. There is usually a trade-off between a very reliable component (low maintenance and high unit cost), against a component with a shorter lifetime (hence higher maintenance) and lower unit cost.

The present assessment focuses on a selected critical component representative of Oscillating Water Column devices: the electric generator. MARMOK is the wave energy technology of focus and IDOM is the company that develops it [6].

The content of the paper is as follows. Firstly, the problem definition is stated together with the scenarios of the analysis. Then, the MARMOK converter and its critical component are defined. Thirdly, the modelling is addressed, where i) MARMOK operational model, ii) the failures and maintenance model, and iii) the economic modelling are described. The paper follows by presenting the first set of results, and finishes addressing conclusions, limitations in the presented modelling and further work.

II. Problem definition and Scenarios

There are three evaluation areas involved in the assessment of the generator's overall performance and lifetime costs:

- *Reliability of the generator*, which can be measured by the metric Mean Time to Failure (MTTF) or the failure rate (λ), as a function of the utilization factor per month and expected lifetime.
- *Energy conversion*, whose key metric is the generator efficiency (η_{gen}) which mainly depends on the load factor (ratio between instantaneous power and nominal power).
- *Power ratio,* as the ratio between maximum power over nominal power (denoted by $\gamma = P_{max}/P_{nom}$), which dictates the number of turbines in operation for each sea state.

This is what we describe as the VALID trilemma (Fig.1).

A small generator provides lower levels of reliability and reduced losses (higher efficiencies) whereas a big generator provides improved reliability (longer lifetimes) and higher losses (reduced efficiencies). In economic and performance terms this means that a small generator (low nominal power) will be cheaper in terms of CAPEX (lower cost), it will also have higher efficiencies (higher energy production) as it will most often operate closer to nominal power, but its lifetime will be shorter (thus OPEX will be higher). And the opposite can be true for a big generator: high nominal power, hence CAPEX will be higher; lower efficiencies, thus reduced energy production; and higher MTTF, thus lower OPEX.

These two conflicting requirements provide a wide design space for improvement. It is believed there is an optimal in between the two extremes. The optimal in terms of costs between a small, cheap generator that fails often and has few losses; and a big, more expensive generator, with more losses and less failures during the WEC lifetime, is the parameter to be explored in this paper.

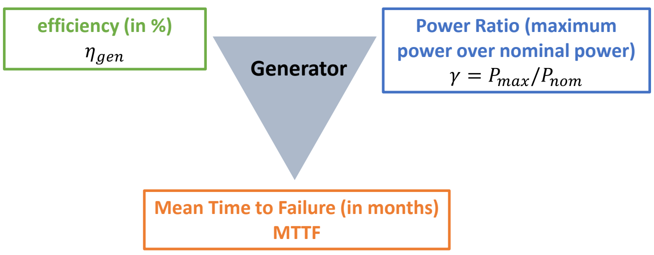

Fig. 1. VALID Trilemma of IDOM case study.

Fig. 2. MARMOK 14-m diameter floating OWC with four PTOs.

To study this, the levelised cost of energy (LCOE) seems the right parameter to look at combined with sensitivity analysis looking into the individual and combined effects of varying the three key parameters defining the generator's performance: generators' MTTF, efficiency and ratio between maximum power over nominal power.

It is also of interest of this study to evaluate which parameters have the highest impact in economic terms, to get an indication of the elements to be further explored and optimised in terms of costs.

To capture the two extremes of the analysis, a baseline scenario is defined based on normalised operational values. This baseline scenario is conceived as a pre-VALID scenario, where baseline parameters are the following:

- $P_{nom} = P_0$, the nominal power of generators;
- $\gamma = n$, the power ratio, i.e. the maximum allowed power over nominal power, and
- MTTF of 3 years.

The values of P_0 and n are confidential for the MARMOK device.

To explore various scenarios, these parameters will be varied in the following range: P_{nom} varying from $0.5P_0$ to P_0; γ varying from n to m (m and n are numbers that are intentionally kept confidential, where m is higher than n); and $MTTF$ varying from 1 year to 3 years. By varying γ from n to m generators are allowed to operate at higher peaks with respect to nominal.

Then, results will be presented in relative terms compared to the baseline scenario.

III. IDOM Case Study and Critical Component

MARMOK is the case study of the work described in this paper (Fig. 2) and the electrical generator is the selected critical component. MARMOK is an offshore floating oscillating water column (OWC) with several power take-off systems (or PTOs) on-board. Each PTO consists of an air turbine, which transforms pneumatic power into mechanical power, coupled to a generator which transforms mechanical to electrical energy [7].

The PTO is not in direct contact with salt water, sitting on top of the converter above water. MARMOK has been designed for operating conditions at the Biscay Bay (BiMEP [8]) and an operating lifetime of 20 years. A wave energy converter of reduced rated power and 5 m diameter was operating without interruption for a 2.5-year period at BiMEP (3 winters) and 12-month at Mutriku test site [9], where the generators did not show any operational problems.

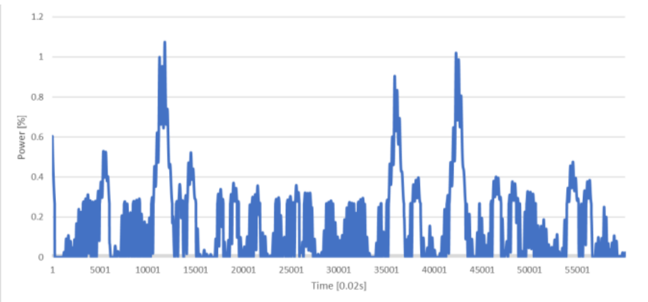

Fig. 3. Power time series (in percentage) of MARMOK operation at mild sea states.

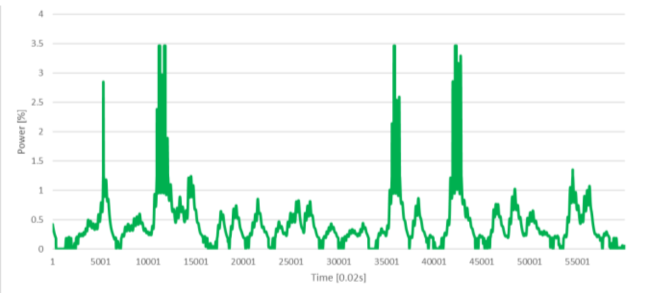

Fig. 4. Power time series (in percentage) of MARMOK operation at intermediate sea states.

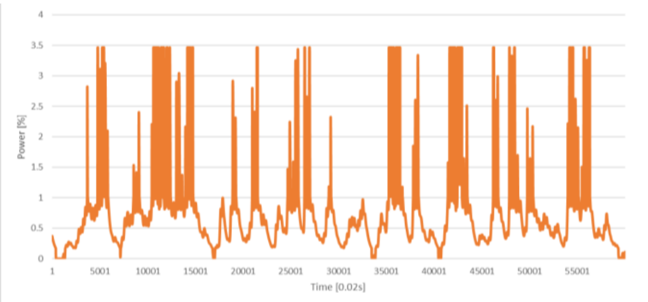

Fig. 5. Power time series (in percentage) of MARMOK operation at strong sea states.

The VALID project focuses on the electrical generator failure. The instantaneous power peaks happening in normal operation are causing electrical loading of the generator, provoking a direct decrease of its lifetime. The operation on high peaks is predominant in winter months when sea states are stronger. In summer months the wave climate is milder, and the peaks are happening more seldom. This is illustrated in Fig. 3, Fig. 4 and Fig. 5, showing the operation at mild, intermediate and strong sea states, respectively, while limiting peak power to 3.5 times nominal power.

The PTO is encapsulated and the generator is manufactured with reinforced insulation. Not only the internal temperature, but also the external environmental conditions (corrosion and temperature) have an impact on the lifetime of the generator [10]. The effects of these working conditions in accelerating degradation are unknown for manufacturers, who are not able to indicate a certain failure rate for the generators. The fact that peak operation is short in time allows for natural refrigeration of the components in between peak operation, which is an advantage towards damage.

VALID pursues the understanding and evaluation of failures in generators that operate a certain percentage of time over nominal power. This type of operating pattern is typically found in OWCs, both floating and fixed. Testing of the generator is ongoing at TECNALIA by looking into how the peaks in operation degrade the generator through a temperature increase in the stator. Degradation will eventually lead to fatal failure of the electrical machine. The degradation model is being developed and will be a valuable output of the project. Ultimately, the VALID project seeks to ascertain the lifetime and subsequently, the design requirements of the generator working under certain operating conditions.

IV. The Modelling

There are three models that work together:

A) *Operational model* describing MARMOK operation depending on the available energy at each sea state, and the generators' nominal and maximum power.

B) *Failure and Maintenance model* describing the operation of each of the four turbines at MARMOK depending on the maintenance operation chosen and the MTTF of the generators.

C) *LCOE model* that relates the size, performance and reliability of the generators to a cost analysis of the WEC.

The case study focuses on the full-scale MARMOK, being 14-meter diameter, with four PTOs and a 20-year design lifetime. The location of the study is BiMEP. The modelling is based on normalised values, and results are provided as a percentage of the baseline values or normalised.

A. Operational model

1) Assumptions

The operational model of MARMOK is deterministic. It has been calculated on a monthly basis, where the power production and the generators' usage rate each month depends on the three variables of the study together with the average available energy (sea states) at BiMEP. The monthly averages have been calculated based on the average available power at BiMEP throughout six years of measured data [11]. The monthly averages of power production are assumed to be the same throughout the project's lifetime.

It is also assumed there are four PTOs on-board the WEC; this is, four turbine-generator groups. The WEC can operate with one, two, three or four PTOs. The number of PTOs or generators working (on or off mode) is an output of the operational model and depends on the energy available in each sea state, the nominal power of each generator and the power ratio, i.e. the maximum power allowed over nominal power.

2) Definition

The model works as follows:

1. Based on the occurrence matrix at BiMEP for every month (based on 6-year measured data, 2009-2015), and the definition of 28 operating sea states in terms of the significant wave height (H_s) and the energy period (T_e) provided by IDOM, a matrix defining the percentage of time of each sea state on a monthly basis is calculated.

2. There are two variable parameters in the model. The model allows to change the nominal power of the generators, P_{nom}, and the power ratio, γ.

3. Based on IDOM's own simulations, the optimal number of working generators for each sea state depending on P_{nom} and γ is calculated. Also, for each month, the percentage of time working with one, two, three or four generators is calculated.

4. Based on the performance of the generators as a function of instantaneous power versus nominal power, the average efficiency for every month and for every sea state is calculated. Then, the annual energy production for each sea state can be calculated based on the number of working turbines and the efficiency at each sea state.

3) Outputs

The model provides for every month over a year:

- Number of generators that work in each sea state.
- Percentage of time that the WEC is working with one, two, three or four generators, and also not working.
- Average efficiency of a generator for every sea state.

B. Failure and maintenance model

4) Assumptions

The maintenance strategy is corrective: a generator is replaced on the same month that it fails. The generator replacement is carried out with a small vessel of the tug-boat type with a crew of four people. This operation can be done in less than 1 day (normally 8 hours per generator) and with significant wave heights below or equal to 1 meter. The MARMOK has an onboard crane on the WEC deck that facilitates this operation. It is assumed that the number of generators required for replacement are available at harbour (i.e. no logistic delay time). Generator's replacement costs assume full-costs of the generator. It is also assumed that a vessel is available (i.e. no vessel waiting time is considered either).

5) Definition

There is one variable parameter in the model: the generator's lifetime or MTTF dictates whether a generator fails or not. The model allows changing its value and is one of the three key parameters of VALID analysis.

The model linearly sums up the rate of usage of each of the four generators, and when the MTTF is reached for any generator this goes into off mode. The number of times throughout the WEC lifetime that each generator goes into failure mode is also measured.

As indicated above, the maintenance operation of a generator replacement can be done in one day, with waves below 1 m significant wave height and a small vessel with four people and a crane on board. The maintenance strategy assumed is corrective: the generator that fails is replaced during the same month that fails, assuming a maintenance vessel is available, a spare generator is also available, and that there is no extra waiting time for weather windows. This is believed reasonable as the model runs on a monthly basis and the results from a weather window analysis in BiMEP carried out within the OPERA project [12] indicate that:

i) The average waiting time for a 24-hour weather window with waves below 1 meter H_s is of one week in summer month, and two weeks in winter months.

ii) The average waiting time for a 48-hour weather window with waves below 1m H_s is of two to three weeks in summer months, and four to five weeks in winter months.

Thus, the generator that was on off mode, after 1 month idle and repaired, is again into on mode. This means that the Mean Time to Repair (MTTR) is 1 month.

Because there are four generators on the WEC, there is some degree of redundancy. Present modelling assumes generator 1 (G1) is the most active by taking all the operations (i.e. G1 operates all the percentages of time that one, two, three and four generators are needed). Then generator 2 (G2) works when two, three and four generators are needed; generator 3 (G3) works when three and four generators are needed; and generator 4 (G4) when the four generators are needed.

Due to the redundancy in the system, the modelling also assumes G3 and G4 can eventually substitute G1 and G2 when either G1 or G2 have failed and G3 and G4 are not in use (i.e. when sea states are not as energetic as for the three and four generators to work, respectively). And similarly, that G4 can substitute G3 if this is on failure mode and the weather conditions are not as energetic as for the four generators to work.

6) Outputs

The model provides the following outputs:

- *Number of failures accumulated throughout the WEC lifetime* ($N_{failures}$) – a parameter that counts the total number of failures, of the four generators together, throughout the WEC lifetime.

- *Number of maintenance operations* (N_{Maint}) – a parameter indicating the total number of maintenance operations accumulated also throughout the project lifetime. The parameter is the sum of all single maintenance operations (only one generator is replaced) and all the combined maintenance operations (where two, three or four generators are replaced). Therefore, note N_{Maint} can be lower than $N_{failures}$

- Energy Production for every month with the chosen operational strategy and dependent on P_{nom}, P_{max} and the $MTTF$.

C. LCOE Model. Cost of Energy Calculations

7) Assumptions

For simplicity, the discount rate is set to zero. This is considered acceptable as the aim is to investigate the relationship among three key parameters – and it is believed that simplicity helps in understanding the modelling outputs. As work advances a more realistic discount rate could be easily included in the calculations.

8) Definition

The Cost of Energy (COE) is calculated according to the following formula, further explained in [13]:

$$COE = \frac{CAPEX + OPEX}{AEP \cdot t} \tag{1}$$

where:

- *CAPEX* is Capital Expenditures of the wave energy converter, in EUR/kW.

- *OPEX* is the Operational Expenditures of the wave energy converter accumulated throughout the WEC lifetime, in EUR/kW.

- *AEP* is the Annual Energy Production at BiMEP of the wave energy converter, in EUR/kWh/y.

- *t* is the lifetime of the wave energy converter, set to 20 years in this case study.

CAPEX is the sum of two terms: reference or baseline CAPEX ($CAPEX_{ref}$), which is a constant value, and the generator costs ($CAPEX_{gen}$), which is proportional to the nominal power of the generators (P_{nom}). Generator costs ($CAPEX_{gen}$) include the costs of the four units.

$$CAPEX = CAPEX_{ref} + CAPEX_{gen} \tag{2}$$

where $CAPEX_{gen}$ is defined by:

$$CAPEX_{gen} = Costs_{gen} \cdot CAPEX_{ref} \tag{3}$$

The cost of the four generators ($Costs_{gen}$, as % of $CAPEX_{ref}$) is calculated through a linear relationship dependent on the nominal power of the four generators (P_{nom}). For the baseline case, the costs of the four generators are about 1.5% of reference CAPEX.

$$Costs_{gen} = 0.015 \cdot \frac{P_{nom}}{P_0} \tag{4}$$

OPEX accumulated throughout the WEC lifetime are defined by the sum of two terms: reference or baseline OPEX ($OPEX_{ref}$), which is a constant value independent of the generators' maintenance, and $OPEX_{gen}$, the term taking into account generators' maintenance:

$$OPEX = OPEX_{ref} + OPEX_{gen} \tag{5}$$

where,

$$OPEX_{gen} = N_{failures} \cdot \frac{CAPEX_{gen}}{4} + N_{Maint} \cdot Costs_{Maint} \tag{6}$$

The parameter *Number of failures in lifetime* ($N_{failures}$) is an output of the *Failure and Maintenance model*, dependent on the operational strategy defined as well as on the MTTF of the generators. The model assumes all failures require an exchange of the generator unit with a new one.

Likewise, the parameter *Number of maintenance operations* accumulated also in the project lifetime (N_{Maint}), is also an output parameter of the *Failure and Maintenance model*, dependent on the operational strategy defined as well as on the MTTF. The model does not make any distinction on the cost of the maintenance operation whether an operation replaces one or more generators, although it takes into account the number of generators to be replaced (higher number of generators implies higher costs).

It is assumed that costs of replacing one generator ($Costs_{Maint}$) are independent on the nominal power of the generator and constant to about 0.2% of the reference CAPEX ($CAPEX_{ref}$) therefore:

$$Costs_{Maint} = 0.002 \cdot CAPEX_{ref} \tag{7}$$

AEP is calculated by summing up the accumulated monthly production of each of the four generators throughout the project lifetime, depending on the sea states at which they operate at; and with the caveat that if one, two, three or the four generators are on failure mode (*off* mode) the maximum energy production of that month, for the given nominal and peak conditions, cannot be produced.

In the figures below, AEP is presented as a percentage compared to the produced energy in the baseline conditions (as indicated throughout the paper, $P_{nom} = P_0$, $\gamma = n$, i.e P_{max} is n times P_{nom}, and MTTF of 3 years).

9) Outputs

The model calculates the COE for various scenarios in the analysis with varying inputs on the three variable parameters, P_{max}, γ and $MTTF$.

V. Results

Fig. 6 represents the efficiency of the generator based on the relationship between instantaneous power and nominal power for the baseline case ($P_{nom} = P_0$). It can be observed that high efficiencies (0.9 and above) are reached as the generator works closer to its nominal power (approximately for values above 0.7 of the nominal power).

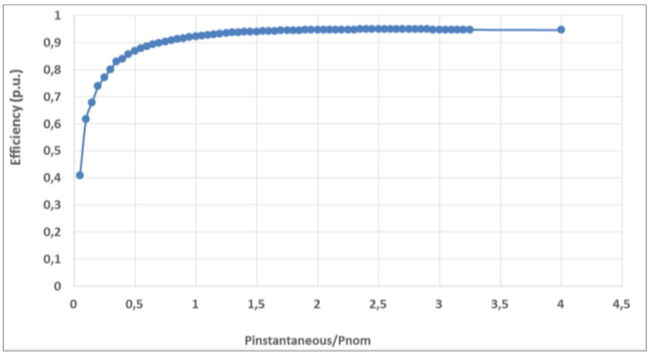

Fig. 6. Typical generator efficiency curve as a function of the load factor (ratio between instantaneous power and nominal power).

A first set of results showing the sensitivity of the performance and COE to the three parameters of the study, keeping constant all the others, are presented.

Fig. 7 shows the relative increase of AEP varying P_{nom} and the power ratio respect to the baseline ($P_{nom} = P_0$ and P_{max} n times P_{nom}). This figure assumes no failures of the generators, hence it shall be interpreted as maximum energy production.

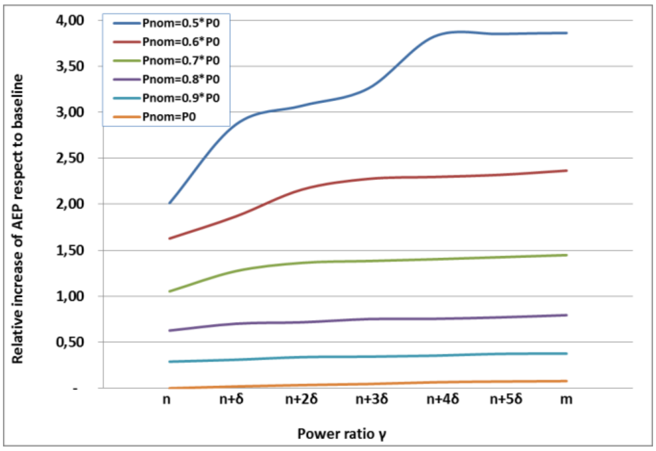

Fig. 7. Relative increase of annual energy production compared to baseline by varying P_{nom} from $0.5P_0$ to P_0 and the power ratio γ from n to m assuming no generators failures throughout the project lifetime.

Fig. 8 shows the percentage change of the COE varying the MTTF from 12 to 50 months and assuming operation with baseline values of $P_{nom} = P_0$ and $\gamma = n$. A bigger influence on the COE is seen for MTTF between 12 to 36 months, which increases the COE by about 6% as lifetime decreases. As MTTF increases beyond 36 months the COE reduction is minimal, with an apparent reduction lower limit of -1% beyond a MTTF of 60 months.

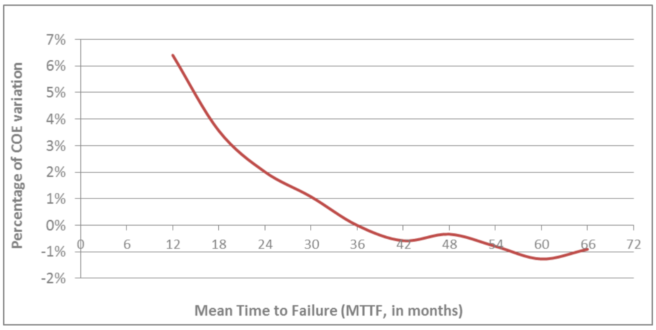

Fig. 8. COE variations (in %) with respect to baseline COE value varying the parameter MTTF from 12 months to 66 months.

Fig. 9 shows that COE decreases as the nominal power of the generators decrease. This is the same trend as shown in Eq. 3 and Eq. 4. The percentage COE change with decreasing P_{nom} is however minimal (below 1%), as $CAPEX_{gen}$ are only 1.5% of total CAPEX.

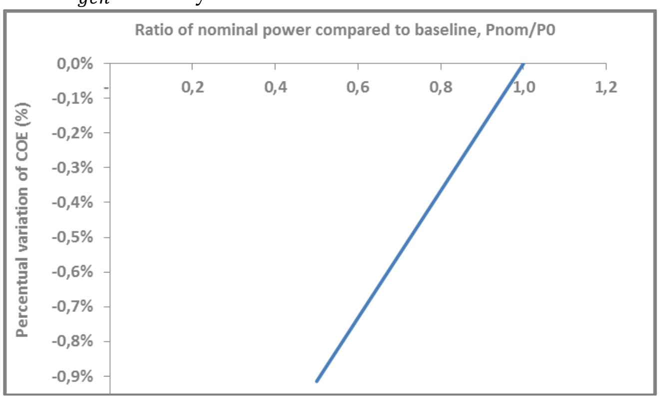

Fig. 9. Relative variation of the COE compared to the baseline COE varying P_{nom} from $0.5P_0$ to P_0.

The following three figures (Fig. 10, Fig. 11 and Fig. 12) show the COE reduction as a percentage relative to the baseline COE, varying P_{nom} from $0.5P_0$ to P_0 and varying linearly the power ratio γ from n to m, with m higher than n, while keeping MTTF constant for each figure. In Fig. 10 MTTF is set at 36 months (i.e. 3-year lifetime of the generators), in Fig. 11 MTTF is set at 24 months (i.e. 2-year lifetime of the generators) and in Fig. 12 MTTF is set at 12 months (i.e. 1-year lifetime of the generators).

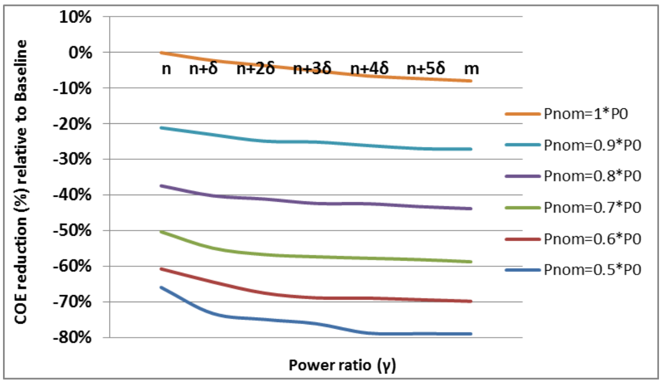

Fig. 10. Relative variation of the COE as a percentage to the baseline COE varying P_{nom} and γ for a constant MTTF of 3-year.

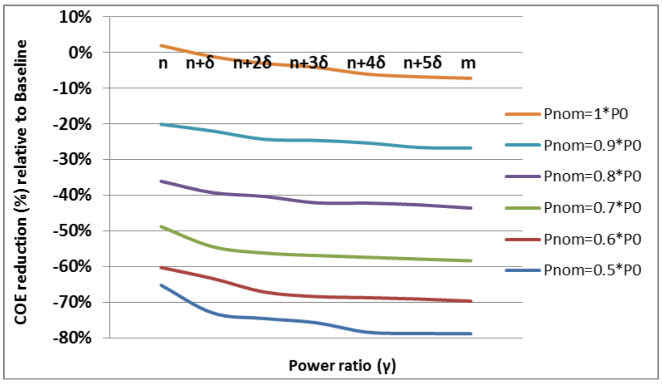

Fig. 11. Relative variation of the COE as a percentage to the baseline COE varying P_{nom} and γ for a constant MTTF of 2-year.

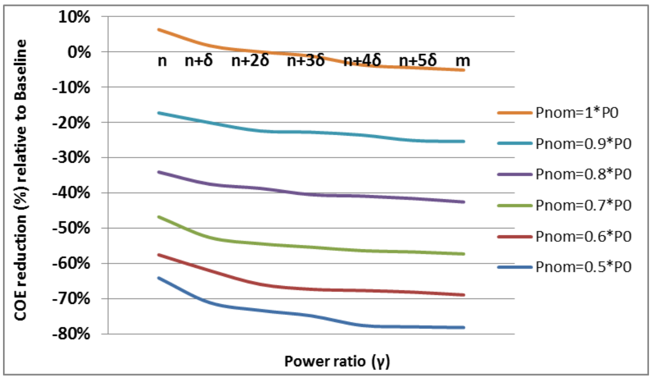

Fig. 12. Relative variation of the COE as a percentage to the baseline COE varying P_{nom} and γ for a constant MTTF of 1-year.

VI. CONCLUSIONS, LIMITATIONS AND FURTHER WORK

D. *Conclusions*

The aim of the paper has been to investigate the potential of reducing the nominal power of the generators while increasing maximum allowed power over nominal power (hence increasing the efficiency of the turbines) in terms of performance and costs.

The first set of results indicate that the gain in higher performance with decreased nominal power and higher maximum power is significant, implying reductions in the COE from 60% to 80% over baseline when reducing by half the nominal power. These results open a large number of very interesting study opportunities and routes to generator's size optimisation. It is also a very interesting finding to see that the MTTF is not the most influencing parameter of the analysis.

The potential in cost of energy reductions is driven by increased energy productions at reduced nominal power and at higher power ratios. The *Operational model* is working with an efficiency model of the generators, which ultimately is describing the efficiency of the generators at different loads (i.e. instantaneous power over nominal power), and hence, the overall energy production. It is acknowledged there are some uncertainties in the efficiency model, which are translated into the results. The model is being reviewed and a first task of mapping the efficiencies of the generator at low loads is ongoing. Although results of the mapping are still preliminary, it can already be seen that the efficiency model utilised in the paper is largely underestimating the generators' efficiency when working at low loads. This translates into the fact that the AEP has been overestimated and the LCOE reductions have been overestimated throughout the modelling.

The models will be therefore reviewed and results will be updated to decrease uncertainty in the calculations. However, the trends in the results presented are reasonable and consistent, indicating there is room for generators' optimisation in terms of costs and performance.

Overall, VALID aims at integrating both reliability and testing methods together with relevant data on component failures early in the design and testing process to ensure that the proposed testing procedure is built upon past experience. This paper aimed at advancing the understanding of MARMOK selected critical components, the electric generator, and its impact on costs. A similar analysis shall be done with the other two User Cases of VALID:

- Hydraulic pump failure (exemplified by the Wavepiston's oscillating wave surge absorber), and
- Dynamic sealing failure (exemplified by CorPower's point absorber).

E. *Limitations and further work*

There are some limitations to the modelling presented in this paper.

Firstly, further modelling can look into different maintenance strategies. The effects of carrying out a Predictive Maintenance Strategy compared to the Corrective Maintenance Strategy assumed in this paper (i.e. no waiting time: replacement when needed) can be investigated. Here, different situations can be studied:

A. Waiting for minimum 2 generators failing, 3 generators failing and all 4 generators failing.

B. Replace G1 and G2 anyhow in summertime.

C. Do not replace any generator on the last year of operation.

D. Apply different maintenance strategy if winter months (no maintenance) or summer month.

Secondly, the *Failures and Maintenance model* is currently assuming that Generator 1 takes all the operations, followed by generators 2, 3 and 4, consequently. And that substitution is only happening when there is a failure. Therefore, G1 is the one failing more often, then G2, etc. It is acknowledged there is a great simplification in this area, as there might be routes of failures optimisation by implementing a different operational strategy. Indeed, if the operation (i.e. the load) was more evenly shared between the four generators (i.e. G1 not always used the most) then presumably generator lifetimes could be extended.

In addition, the present model assumes a linear failure model of each generator – only dependent on the total time of usage, and independent on the type of operation and stress that it is exposed to (e.g. the life model is independent on the power ratio, i.e. the ratio of maximum power over nominal power). It is known there is a relationship between degradation and stress, and the coefficients and type of relationship are currently being studied by TECNALIA [14]. As data comes from the hybrid testing, the present modelling will be updated and refined to account for a realistic degradation rate of the generators.

It is also recognised that these results are dependent on the selected site for the study and its wave climate.

Lastly, as part of VALID it is also believed that by introducing hybrid testing at early stages in the development process, the overall uncertainties can be reduced. Further work is envisaged evaluating the degree of uncertainty in the LCOE calculations related to the assumptions made in the models. For that, the VMEA methodology will be utilised [15]. RISE has carried out a similar exercise within VALID [16] and aims to collaborate also in this activity.

ACKNOWLEDGEMENT

This work has been funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927 (the VALID Project – Verification through Accelerated testing Leading to Improved wave energy Devices).

REFERENCES

[1] D. M. Ingram, G. Smith, C. Bittencourt-Ferreira, and H. Smith, 2011. *Protocols for the equitable assessment of marine energy converters*. University of Edinburgh, Institute for Energy Systems, School of Engineering,

[2] DTOceanPlus, 'DTOceanPlus - Advanced design tools for ocean energy systems innovation, development and deployment'. https://www.dtoceanplus.eu/ (accessed May 21, 2023).

[3] RiaSor, 'RiaSor - Reliability in a Sea of Risk'. http://riasor.com/ (accessed Jun. 15, 2023).

[4] P. Johannesson, 2019. 'Reliability Testing', Deliverable 3.6 to the WaveBoost Project. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c8e7279f&appId=PPGMS

[5] VALID, 'VALID - Verification through Accelerated Testing leading to improved Wave Energy Design', https://www.validhtp.eu (accessed May 21, 2023).

[6] 'Wave Energy Converter Prototype - MARMOK A-5', *IDOM*. https://www.idom.com/en/project/wave-energy-converter-prototype-marmok-a-5-2/ (accessed Jun. 15, 2023).

[7] R. Rodriguez Arias *et al.*, 2016. 'Requirements for Offshore Operations for Wave Energy Converters'. Deliverable 6.1 to the OPERA Project.

[8] 'BiMEP – Biscay Marine Energy Platform'. https://www.bimep.com/en/ (accessed Mar. 22, 2021).

[9] BiMEP, 'Technical Characteristics – Mutriku site'. https://www.bimep.com/en/mutriku-area/technical-characteristics/ (accessed May 21, 2023).

[10] E. Robles *et al.*, 2023. 'Definition of Generator Thermal Fatigue Testing', Deliverable 4.1 to the VALID Project [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e81cc417&appId=PPGMS

[11] 'Key documents – TRLPlus'. https://trlplus.com/key-documents/ (accessed Jun. 15, 2023).

[12] J. Lopez-Mendia, P. Ruiz-Minguela, R. Rodríguez, P. Etxaniz and B. De Miguel, B. Flannery, P. Goodwin. 2017. "Operational model for offshore operations of wave energy converters". Deliverable 6.2 to the OPERA project.

[13] Têtu, A.; Fernandez Chozas, J. 2021 "A Proposed Guidance for the Economic Assessment of Wave Energy Converters at Early Development Stages". Energies 2021, 14, 4699. https://doi.org/10.3390/en14154699

[14] J. Lekube *et al.*, 2023. 'Description of UC#2 hybrid testing platform', Deliverable 4.2 to the VALID Project.

[15] P. Johannesson *et al*. 2019. "System reliability Evaluation". Deliverable 6.3 to the WaveBoost project. [Online] Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c8e06084&appId=PPGMS

[16] P. Johannesson et al., 2023. "Report on Uncertainties in Testing Methodologies: a Guideline on Uncertainty Quantification in Hybrid Testing". Deliverable 1.3 to the VALID project.