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Preliminary Assessment of a Semi-Submersible Floating Wind Turbine Combined with Pitching Wave Energy Converters

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Abstract— This paper synthesizes the technical feasibility study carried out for a hybrid ocean energy converter. The solution envisaged involves a 100m large semi-submersible platform designed with five columns and equipped with floating pitching Wave Energy Converters (WECs). This floating structure is mounted with a 5MW wind turbine. The present study covers power performance estimations and structural analysis. The first section describes the “Wave to Wire” model programmed in both frequency and time domain. The mathematical and hydrodynamic assumptions are highlighted together with the numerical model. The second part starts with the assessment of the performances of this device, carried out using in-house simulation codes. Based on combined wave and wind resources, the annual average absorbed power figures are compared with published results for existing ocean energy converters. The total rated power of the combined system reaches 10MW. Eventually, the last section approaches practical topics, directly related to the capital and operational costs inherent to an industrial development phase. The total steel mass of the semi-submersible is estimated first, from structural calculations carried out for a selection of 3D static loads cases. Then, the extreme loads from the WECs are taken into account for a second design phase.

Keywords— Wave energy converter, floating wind turbine, combined energy platform, structural analysis.

I. INTRODUCTION

The *MARINA Platform* project is a European initiative created to bring expertise from offshore wind industries together with ocean energy specialists, in order to reduce costs for deep water offshore platforms. Additional information is available on the project website [1].

The present study lies within the second phase of the project, addressing the feasibility of a set of pre-selected concepts. It essentially focuses on one particular solution: the “THyP”. This Truss Hybrid Platform is a five columns semi-submersible, mounted with 5MW wind turbine on the central rear column. Pitching Wave Energy Converters (WECs) are installed on the wave facing sections, and attached to the beams linking the front three columns. A 3D picture of the

system is shown in Fig 1, while the main dimensions are displayed in TABLE I.

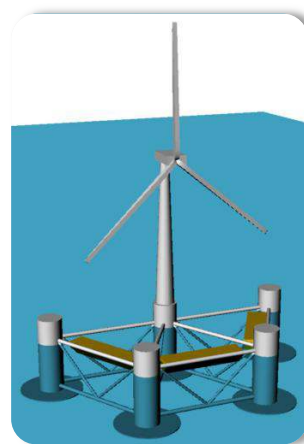


Fig 1. 3D view of the THyP semi-submersible combined platform

Another multi-bodies large combined platform has been studied in [2]. Even though the power capture compared well with existing concepts, its fully novel design led to a relatively high cost of energy and project feasibility. The present THyP concept can be seen as the next iteration in the process. It is inspired from existing floating wind concepts [3], with additional columns aiming to increase the available absorption surface. The pitching WECs have been tested by different industrial developers, some being at a fairly mature stage ([4] for instance). The THyP concept is expected to combine the advantages and fairly high Technology Readiness Levels (TRL) from both technologies

The first section of this paper will focus on the system description. The dynamic equations required to build the Wave to Wire (W2W) model are then detailed, relying on proven modelling methods [5]. The in-house solver [6] had to be updated in order to take into account the unusual degrees of freedom of the WECs. Additional nonlinear forces such as the

wind loads, the viscous effects and the end-stops have also been implemented in the time domain code.

TABLE I: MAIN DIMENSION of the THyP.

Properties	Ref	Value	Units
Platform			
Width	R	120	m
Draft	D	22.5	m
Displacement	V	10930	t
WECs			
WECs number	N	12	-
Width	W	9	m
Wetted surface	S_0	180	m^2
Mass	m_i	235	t
Wind Turbine			
Rotor diam.	d_{rotor}	126	m
Nacelle height	z_N	100	m

In the second section, the initial performances of the platform are assessed for a few different sites in Europe. A brief set of numerical tests have been carried out in order to validate the different models, in both frequency and time domain. Finally, the power matrix is displayed together with the mean annual power outputs. The performances of the THyP can eventually be compared to existing devices from the wave and the wind energy domains.

The last section approaches practical topics, directly related to the capital and operational costs inherent to an industrial development phase. The total steel mass of the semi-submersible is estimated first, from structural calculations carried out for a selection of 3D static loads cases. As a second step, additional loads are added to the front beams reflecting the presence of WECs. The design had been modified to sustain these loads in extreme conditions.

II. WAVE TO WIRE MODELLING

The numerical modelling approach is extensively described in [2] and [5]. Therefore, the dynamic equations are not recalled in this paper, focusing on the physical description of the system.

A. Working principle and system description

At first, waves are supposed to be unidirectional, propagating against the x direction (Fig 2).

The variable θ_i^j refers to the relative angle motion of the WEC(i,j) as shown in blue, in Fig 2 and Fig 3. The first index corresponds to the arm where the WEC is located ($i \in [1,2,3]$), whereas the second index notices the position of the WEC on the arm ($j \in [1,2,\dots,N]$ with $N=4$ in this study). Each independent absorber is linked to the platform through a Power take Off (PTO) system, transforming the mechanical power into an electrical output

The variables x, z, θ will refer to the motions of the platform in surge; heave and pitch. The behaviour of the system can be fully described with 15 degrees of freedom (DOFs).

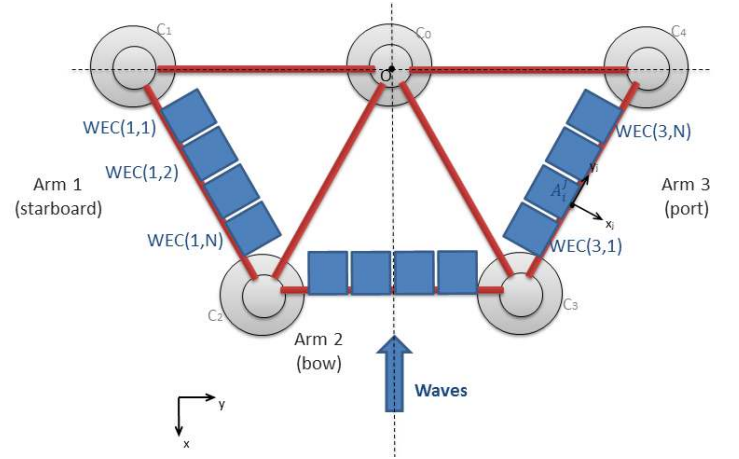


Fig 2. Top view sketch of the THyP, with nomenclature.

The implementation of the hydrodynamic forces depends on the numerical capabilities of the hydrodynamic software. The in-house BEM code NEMOH was used in this study to calculate the hydrodynamic coefficients. This new version of the solver enables the user to implement additional DOFs. The rotation of each WEC(i,j), around the hinge A_i^j , will be modelled as an additional degree of freedom (read section II.C)

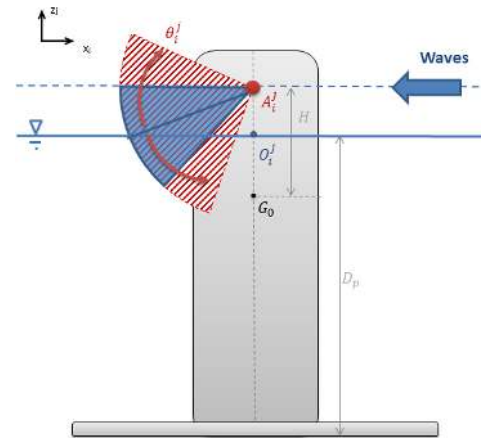


Fig 3. Side view sketch of a column and a pitching WEC.

B. Numerical modelling

TABLE II summarizes the different forces implemented in the W2W model and detailed in [7]. Additional nonlinear loads are implemented in the time domain model.

TABLE II: SUMMARY of the LOADS IMPLEMENTED in the MODEL.

Loads	Linear	Details
Excitation	x	Expressed at the gravity center of the 13 bodies (considered independent).
Radiation	x	The loads represent the interactions between the 51 DOFs (4 DOFs for each WEC and surge/heave/pitch of the platform). Using the in-house software NEMOH.

Hydrostatic	x	Calculated at the buoyancy center of each body by integration of the pressure at the equilibrium after a small perturbation.
Gravity	x	Vertical force in the global coordinate system applied at the gravity centre of each body.
PTO	x	The hydraulic system is represented by stiffness and damping coefficients. The force is applied at the gravity center of the WECs and directly proportional to the angular motion θ_i^j and velocity $\dot{\theta}_i^j$.
Moorings	x	Initially represented as a horizontal spring and a static contribution to compensate for the horizontal static wind force.
End stops		The maximum angular motion is set to 20deg by default. A large stiffness value is applied through an Heaviside function when $\theta_i^j > \theta_{max}$.
Ballast	x	The ballast is considered as an additional point mass body, in order to balance the horizontal wind and gravity forces applied on the Wind Turbine (WT).
Wind		The TDHMILL method relies on lookup tables of the wind thrust, for a given value of the relative wind speed at the Nacelle.
Viscous		The heave plates of the semi-submersible platform are considered as Morison elements. A vertical force proportional to the relative fluid velocity is applied at the keel of each column. The drag coefficients are taken from [8].

C. Additional degrees of freedom

The rotational degrees of freedom of the WECs on the port and starboards arms of the platform are not conventional in the context of the seakeeping of offshore structures. The axis of rotation is neither the x, y or z-axis corresponding to the yaw, pitch and roll motions but a combination of the x and y axis. Thus, one has to use a generalized mode approach as explained in [9]. The in-house BEM solver NEMOH was used. It solves the well-known linear free surface boundary value problem for the velocity potential ϕ for any given user specified function of space $f(M)$ for the boundary conditions on the body surface.

In case of the THyP, there are 12 additional degrees of freedom in contrast with usual offshore structures. Thus, there are 12 additional radiation problems to solve for which the body condition is:

$$f_j^i(M) = \begin{cases} (\overrightarrow{A_j^i M} \times \overrightarrow{r_j^i}) \cdot \vec{n} & \text{if } M \text{ belongs to the wetted surface of WEC}(i,j) \\ 0 & \text{if not} \end{cases}$$

Once the potential has been determined, the solver allows calculating the forces and moment forces by pressure integration at any location. It is done at the hinge and at the gravity centre of the platform. Thus, results of the

hydrodynamic solver are the necessary radiation coefficients and excitation forces.

As far as the linearized hydrostatic coefficients are concerned, an analytical formula was derived from the direct integration of the static pressure on the WECs wetted surface.

D. Modal Analysis and stability

The calculation of the eigenvalues of the stiffness matrix of the full system provides valuable information concerning the static stability of the platform. If the overall stiffness matrix is not positive definite, i.e. all the eigenvalues are not positive, unstable behaviour can be expected (according to [10]). Taking into account the hydrostatic, gravity and mooring coefficients, one can determine the minimal PTO stiffness, $K_{PTO_{min}}$, required to obtain a stable static equilibrium.

This stability issue is one example of the strong coupling between the different degrees of freedom of the system. The classical formula used to determine the natural periods of the platform could not be applied for such a complex system. The modal analysis method described in [11] was directly applied to the system. The solutions of the generalized damped eigenvalue problem represent the natural modes of the system, highlighting the following properties of the THyP:

- The WEC modes are strongly influence by the three DOFs of the platform (surge, heave, and pitch).
- The pitch mode is strongly damped.
- The eigen-frequencies of the system can shift significantly depending on the system parameters, such as the PTO stiffness and damping.

This last item has strong consequences on the power absorption results. Indeed, the modal analysis showed that the stability of the platform and its eigen-frequencies depend on the PTO settings. In other words, while optimising the power absorption, the PTO stiffness and damping coefficients will have to be adjusted with care in order to ensure the stability of the platform.

III. INITIAL POWER RESULTS

A. Environmental input data

Within the MARINA project, full environmental data have been provided for a few selected European sites. The following section will focus on the “site 14” which corresponds to a point located 30km from the Norwegian coasts, where the water depth is approximately 200m (GPS coordinates : 61.85N, 4.23E).

A full 3D calculation taking into account the statistical variability of the wind speed, the significant wave height and the peak wave period, was presented in [2]. However, it appears that for large combined platforms, selecting the most probable wind speed for a given sea state provides annual average power values very close to a full 3D environmental study. Therefore, a time domain run was carried out for each cell in the scatter diagram with the most probable associated wind speed. These two scatter diagrams are presented in the left column of Fig 4.

B. Non linear time domain power results

The power outputs from the numerical simulations are shown in the right column of Fig 4. As a matter of consistency, the total rated power of the WECs is set to 5MW. Furthermore, the efficiency of the transfer from mechanical to electrical power through the PTO is set to 65%.

These two matrices show similar trends and amplitudes. Knowing that they represent the absorption capabilities of the platform before taking into account any environmental statistics, it emphasizes the balanced energy contributions. The non-linearities appearing on the WEC power matrix

essentially result from a modification of the PTO parameters in each cell of the scatter diagram. Even though optimizing for every sea state does not improve the annual average power significantly, it allows reducing the number of impacts on the end-stops. Indeed, a healthy operational strategy would aim for a minimal use of the end-stops, which can be considered as a difficult topic in terms of fatigue.

Eventually, the annual average wave power is obtained multiplying the occurrence matrix (left) and the power matrices (right). Another site is considered, taken from the project database, and marked at 40km from the Portuguese coasts (GPS coordinates: 42.13N, -9.40E). The annual average results for these two sites are summarized in TABLE III.

TABLE III: ANNUAL AVERAGE POWER RESULTS for the THYP.

	Units	Site 14	Site 3
Wave resource	[kW/m]	50.5	45.1
Wind resource	[W/m ²]	750	370
Electrical WEC power	[MW]	1.47	1.32
Electrical Wind power	[MW]	1.55	1.33
Total electrical power	[MW]	3.02	2.65

The annual average wind power figure obtained numerically are very close to the expected results for a 5MW rated turbine, considering a 30% capacity factor.

Essentially, the contribution from the WECs is about 50% in terms of electrical annual average power, for the two sites considered.

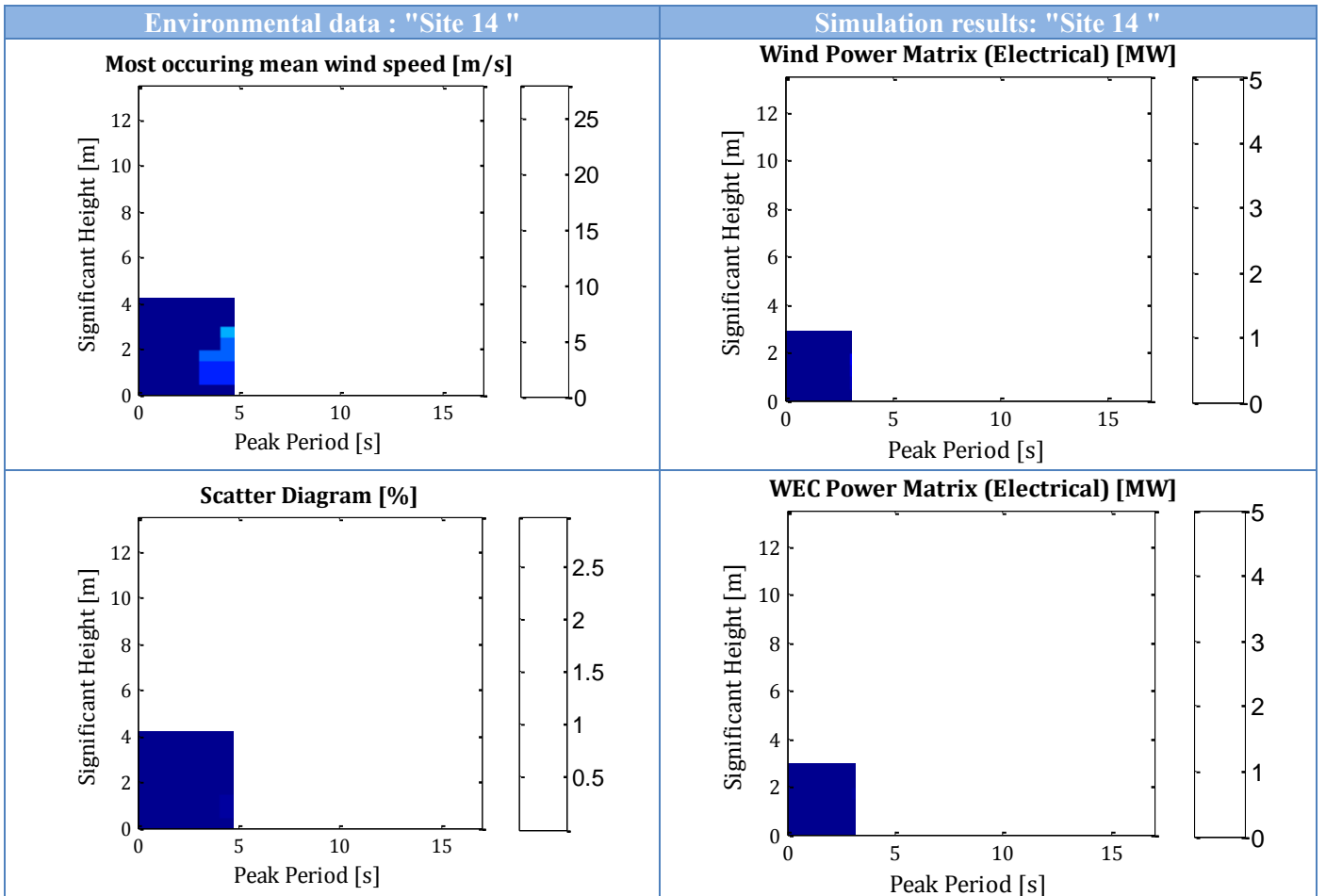


Fig 4. Time domain power results and input scatter diagrams.

C. Benchmarking

The results presented in the previous section were used internally in the MARINA project, in order to compare with other hybrid concepts. However, it seems legitimate to compare the power production of this platform with existing devices from the wave and wind energy domains.

According to [5] the power produced by different types of WECs can be estimated knowing their capture width ratio. The environmental data selected for this comparison corresponds to the French site of Yeu. TABLE IV displays together the mechanical power absorbed by the THyP WECs and by concepts similar to the Oyster (fixed pitching flap), the Wavestar (oscillating buoys) and the Wavebob (heave oscillating bodies).

TABLE IV: POWER COMPARISON BETWEEN the THyP and EXISTING WECs.

Site - Yeu	Units	THyP WEC	Oyster "like"	WaveStar "like"	Wavebob "like"
Resource	[kW/m]	26.2	22.4	22.4	26.2
Abs. power	[MW]	1.76	0.44	0.28	0.19
Capture width	[%]	61	72	17	36
Energy / V	[MWh/m ³]	1.16	1.0	1.5	0.3
Energy / Stot	[MWh/m ²]	1.18	1.9	0.56	0.79

Furthermore, the total power produced by the platform can be compared with floating wind technologies, assuming typical capacity factors of 30% (TABLE V).

TABLE V: POWER COMPARISON BETWEEN the THyP and EXISTING FLOATING WIND TUBRINES.

Site - Yeu	Units	HyWind "like"	Windfloat "like"	THyP Tot
Elec. Power	[MW]	1.5	1.5	2.40
Energy / V	[MWh/m ³]	1.88	2.8	1.6
Energy / Stot	[MWh/m ²]	1.7	0.85	1.61

The total absorbed power is significantly higher for the WECs of the THyP, even though the results are comparable in terms of performance. Similar trends can be observed when all the contributions are taken into account and compared with floating wind devices.

In other words, the THyP can produce a large amount of power thanks to its large dimensions. However, the size can also become an economical drawback. Therefore, a structural analysis phase is required in order to estimate the steel mass of the THyP.

IV. STRUCTURAL ANALYSIS

In order to estimate the economic feasibility of the THyP concept, a preliminary structural analysis has been performed. The objective of this analysis is to estimate the amount of steel required to withstand the external loads.

A. Initial structural design and load cases

First, the preliminary structural design of the platform was based on the general arrangement described in section I (TABLE I), and is inspired from existing concepts of offshore turbine floating foundations, such as WindFloat [3] and the Dutch tri-floater [11].

The columns have a diameter of 10.7 m and are designed as SPAR structures. The total steel mass of one column is 135 tons (excluding heave plates and ballast). The heave plates have a 28 m diameter, and weight 90 tons each. The columns are linked together by a set of horizontal beams and oblique braces, which properties are:

- beams: diameter 1.8 m, wall thickness 36 mm ;
- braces: diameter 1.6 m, wall thickness 32 mm.

The mass of ballast required was tuned to ensure that the total mass of the platform equilibrates its displacement. The large inner column volume allows ballasting with concrete or/and freshwater, leaving the door open to a stabilization mechanism through the transfer of water between columns. TABLE VI summarizes the mass assessment of the platform.

TABLE VI: MASS ASSESSMENT of the THyP.

	Description	Total mass (tons)	Proportion (%)
Platform	Columns	573.7	5.15
	Covering columns	102.34	0.92
	Heave plates	447.0	4.02
	Beams	861.7	7.75
	Braces	424.3	3.81
Turbine	Tower	318.6	2.86
	Rotor / Nacelle	350.0	3.14
Add. steel	5% surcharge	153.9	1.38
Platform	Ballast	7899.41	70.97
THyP	TOTAL Mass	11131.07	100 %
THyP	TOTAL Displacement	11131.07	100 %

The steel properties have been chosen in agreement with relevant offshore standards [11 - 14]: characterized by a standard density of 7850 kg/m³ and a yield strength of 345 MPa.

This preliminary design was checked, to ensure its compliancy with offshore standards for relevant load cases. Sagging load cases were considered in the analysis. Given the shape of the platform and its purpose (capturing wave from a large direction range), four cases with different wave headings were studied, adjusting the wavelength to the platform dimensions (Fig 5). The associated 100 year return significant wave height is estimated thanks to environmental models generated from hindcast data, provided within the frame of MARINA project (ref. III-A). TABLE VII summarizes the

load case conditions for a specific site located 30km from the Norwegian coasts, where the water depth is approximately 200m (GPS coordinates : 61.85N, 4.23E). For Load case 3, the 100 year wave height leads to a steepness over the conventional breaking limit. The value of Hmax had to be corrected before running the simulations.

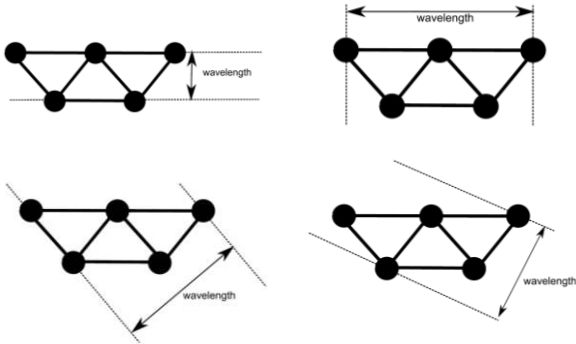


Fig 5. Representation of the Load cases 1 to 4 (wave headings 0°,90°,60°,30°).

TABLE VII: LOAD CASES CONDITIONS.

Load cases	Wave length	Wave period	Hmax	Wave steepness	Corrected Hmax
<i>units</i>	[m]	[s]	[m]	[-]	[m]
1	43.3	5.3	4.25	0.098	4.25
2	100	8.0	6.10	0.061	6.10
3	86.6	7.5	14.86	0.172	12.12
4	75	6.9	9.36	0.125	9.36

B. Structural analysis (without WEC loads)

The THyP was studied through a static finite element analysis. The platform was modelled using tubular beam elements, and thus the columns were represented in a simplified way. This method gives a reasonable accuracy for the global deformations of the structure and for forces in beams and braces. Local results at joints involving the columns are considered unrealistic; they were not taken into account in the analysis.

Stress results in members and joints involving the beams and braces are checked using the API RP 2A-WSD standard [16].

The loads applied in the analysis are the following:

- Gravity ;
- Turbine loads (moment at the tower base, assuming a maximum thrust on the rotor and wind collinear with waves) ;
- Buoyancy forces; for each load case, the draft and buoyancy forces are calculated, based on hydrostatic analysis (Fig 6).



Fig 6. Hydrostatic analysis for load case 3.

TABLE VIII: UTILIZATION RATIOS in MEMBERS and JOINTS.

Load cases	Case 1	Case 2	Case 3	Case 4
Member Axial	0.067	0.194	0.459	0.318
Member resultant Bending	0.164	0.196	0.221	0.205
Joint Axial	0.069	0.190	0.440	0.312
Joint In Plane Bending	0.109	0.115	0.126	0.120
Joint Out Plane Bending	0.008	0.028	0.043	0.031

TABLE VIII summarizes the maximum utilization ratios found by static analysis in the members and joints of the structure for the 4 load cases. A ratio higher than one indicates that the corresponding force is higher than the value authorized by the standards. No ratio is found higher than one, which means that the preliminary design is satisfying, when the loads from the WECs are not considered.

The analysis reveals that Load case n°3 is the most critical. This is due to a combination between:

- A very large wave height;
- A very large distance between the wave crests which support the two ends of the platform.

Therefore, two columns are situated at a wave trough, resulting in large deformations in the structure (Fig 7). It appears that the largest deformations occur on the upper beam, because their weight is not compensated by buoyancy forces. TABLE IX summarizes the maximum structural forces found in the members.

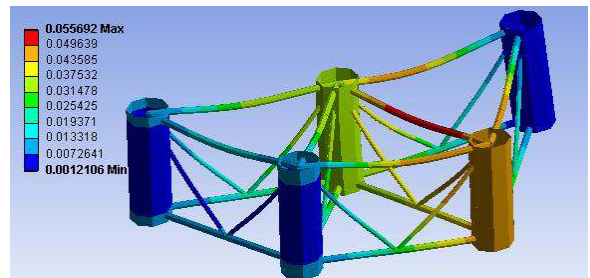


Fig 7: Deformations of the structure for Load case 3.

TABLE IX: MAXIMUM DEFORMATIONS and FORCES for CASE 3.

Description	Value
Maximum deformation [mm]	56
Maximum axial force [N]	1.18E+07
Maximum bending moment [N.m]	8.25E+07

C. Structural WEC loads

The next step of the analysis aims at integrating the structural loads from the WECs on the horizontal beams supporting them. To assess the most conservative case, Load case n°3 was investigated. The wave loads were extracted from non-linear, time-domain wave to wire simulations (ref. section II.B.). The maximum reactions of the WECs at the hinge were taken from a time domain run and multiplied by a factor 1.3, in order to take into account the statistical variability [17]. The orders of magnitude of these loads are:

- Vertical force : 2.7 104 kN
- Horizontal force : 2.5 103 kN
- Pitching moment : 2.12 104 kN.m

Including these loads in the analysis leads to very high, non-admissible utilization ratios. The highest ratios were obtained in the upper beams, which are significantly deformed by the vertical forces (up to 3.7 m).

Table X: UTILIZATION RATIOS for LOAD CASE 3, WITH and WITHOUT WEC LOADS.

Description	Without WECs	With WECs
Member Axial	0.459	4.834
Member Resultant Bending	0.224	16.37
Joint Axial	0.440	5.678
Joint In Plane Bending	0.126	1.546
Joint Out Plane Bending	0.043	0.709
Joint Combined (Axial + Bending)	0.489	8.348

As a first and basic approach, it was decided to iterate on the properties of the beams and braces, in order to reach utilization ratios lower than one. It led to very thick and unrealistic members (Table XI, Fig 8), increasing the steel mass of the structure by 210 %.

Table XI: BEAM PROPERTIES for the FINAL STRUCTURE.

	Outer Radius [m]	Inner Radius [m]	Thickness [m]
Upper beams supporting WECs	2.2	2.1	0.1
Other upper beams	1	0.9	0.1
Lower beams	0.9	0.8	0.1
Braces	0.85	0.75	0.1

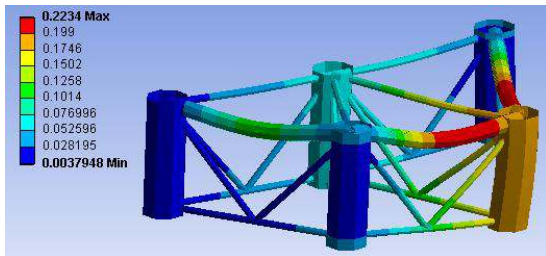


Fig 8: Deformation of the final structure, for load case 3, including the WEC loads.

This preliminary structural analysis proved the significant role played by the WECs in dimensioning the structure, even

compared with the turbine or gravity loads. Therefore, they must be considered early in the analysis. The final design reached in this analysis is not satisfying from a structural point of view, as beam sections are extremely thick, and lead to a very large steel mass. It is recommended to design a more elaborated truss, in order to distribute the loads more equally within the structure, and optimize steel weight.

V. CONCLUSIONS

This study summarizes the feasibility analysis of a combined wind and wave energy platform. The selected concept is a five column semi-submersible, set with 12 pitching wave energy converters attached on the wave facing braces. A 5MW wind turbine of the NREL type is installed on the central rear column.

The device working principle was explained first, prior to a brief presentation of the numerical coupled hydro-aero-dynamic model. The power production was estimated with non-linear time domain runs, for a few different sites over the European coasts. For a Norwegian site, the annual average electrical power provided to the grid can reach 3MW, with fully balanced contributions from the wind and wave absorbers.

The assessment of the technical feasibility required a preliminary structural analysis. The initial design of the semi-submersible platform, mounted with the wind turbine, is satisfying regarding the industry standards. However, the implementation of the WECs on the beams implies significant design modifications leading to a large increase of the capital expenditures. Nevertheless, the main objective was to demonstrate the feasibility of a combined concept based on existing and proven technologies. Further iterations in the design process are expected to reduce the project costs.

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