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Techno-economic designs of hybrid wind-wave offshore energy systems and comparison with TOPSIS analysis: an Italian case study

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Abstract. This study assesses multiple hybrid wind and wave floating offshore systems, utilizing a preliminary approach for dimensioning and the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) analysis method for comparison. It aims to provide an initial evaluation of diverse concepts, emphasizing state-of-the-art combinations of Floating offshore Wind Turbine (FOWT) with Wave Energy Converters (WECs). The criteria for evaluation include system cost, power extraction, WEC integration, dynamic and environmental responses, offering a comprehensive view of performance, economic viability, constructability, operational efficiency, and environmental impact. The findings, derived from the application of these methodologies, are informed by an Italian case study, enriching the insights and illustrating the practical implications of the evaluated hybrid systems within the Italian context. Preliminary results suggest a tendency for semi-submersible platforms to be more suitable for combined with WEC devices.

Keywords: Offshore renewables, wind and wave renewable hybrid system, TOPSIS, Nautilus, OOcstar ,Wavestar.

1. Introduction

The sustainable energy solutions have prompted significant progress in the offshore sector wind energy production. Harnessing the abundant and reliable wind resources offered by the oceans presents a crucial opportunity to transition towards a cleaner and more sustainable energy future. Floating Offshore Wind Turbines (FOWT), with their capacity as a renewable energy source due to higher wind speeds and extensive available areas, emerge as a compelling alternative to onshore wind. However, the significant barrier to fully unlocking this potential lies in the relatively high costs associated with offshore wind energy solutions. Effectively addressing these cost challenges is essential for optimizing the efficiency and feasibility of offshore wind initiatives. Although offshore wind and wave energy converters are often developed separately, as done respectively in [1] there are significant synergies that can be exploited between such technologies, including cost-sharing and power production variability compensation. Hybrid solutions for offshore wind and wave energy have been attracting industrial interest, aiming to create more competitive devices than offshore wind alone. W2Power is one of the most successful examples of a floating hybrid wind device [2], combining two wind turbines in the front corners and multiple point absorber WECs on the same semi-submersible platform. Another example of a floating hybrid platform is the Poseidon P37 platform, developed by Floating Power Plant Ltd [3] the wave absorbers consist of a front pivot hinged absorber that can absorb both the push and lift of the wave into one mechanical movement, which aliments the Power take-off (PTO) chain. The PTO system is an oil-based multi-cylinder hydraulic system connected directly to the hinge axis of the absorbers. It is worth noting that the evaluation of these hybrid solution in various past papers has often been discussed [4]. The majority focused extensively on single assessment perspectives, such as comparing extracted power or economic indices equivalents (LCOE and NPV), without considering a global vision. This paper, however, aims to outline a preliminary method for evaluation, considering this renewable solution from multiple perspective to provide a more realistic assessment and to integrate not only technical aspects but also environmental and social effects. This approach aligns with the works [5], wherein environmental and social impacts were also taken into consideration, to evaluate the best solution of floating substructure for floating offshore wind turbine. Within this context, there emerges a pressing demand for a thorough assessment of diverse hybrid wind and wave floating offshore systems. This manuscript aims to address this need by conducting a preliminary evaluation of various concepts, with a specific focus on combinations of platforms with WECs. By distilling and scrutinizing information gleaned from existing hybrid concepts, this study serves as a discerning filter to identify and evaluate promising designs. After an introductory section, this paper is structured into four sections: Section 2 proposes the methodology and the Material, with explication on the criteria at the base of the TOPSIS analysis; then, in the Section 3 the theory to analyze static and dynamic features of the hybrid energy system is elaborated and applied. Finally, results are reported in Section 4, summing up the remarks presented.

2. Material and method

The paper aims to evaluate the potential of combining wind and wave energy in offshore locations in Italy. The methodology (Figure 1) involves analyzing resource assessments to identify correlations between wind and wave parameters. Key inputs include mass, geometry, and cost features of hybrid platform subsystems. Numerical analyses using the MOST tool assess [6, 7] system dynamics and Annual Energy Production (AEP). The results inform a TOPSIS analysis comparing hybrid solutions across different scenarios for each identified site.

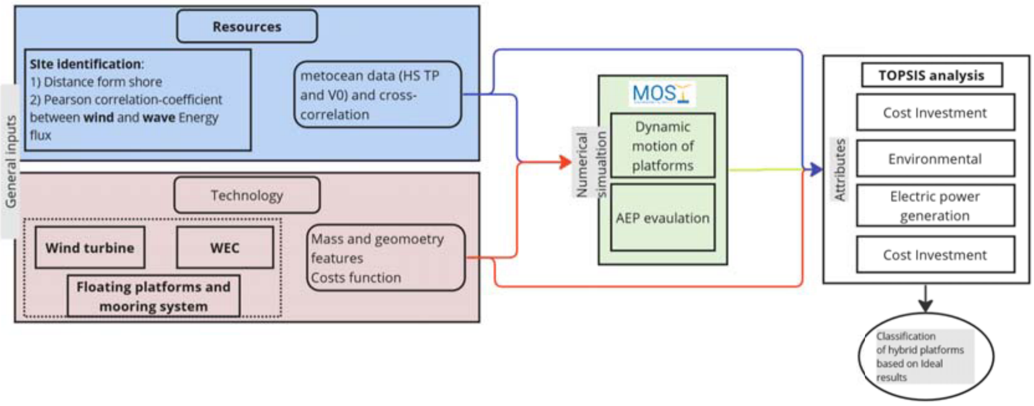
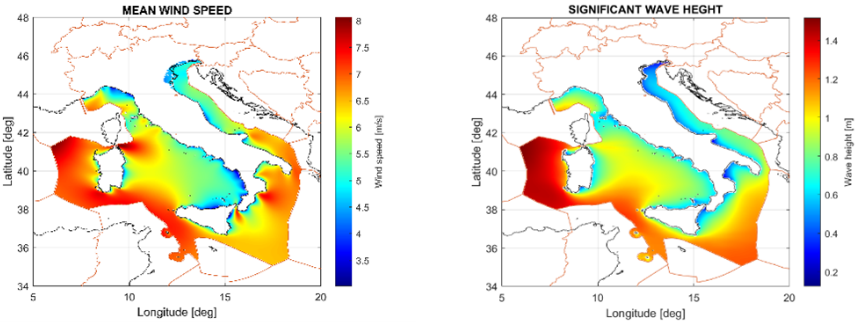


Figure 1: Applied methodology workflow

2.1. Wind and Wave resources analysis

A comprehensive dataset spanning twenty-one years (from 2001 to 2020), encompassing mean wind speeds (form the CERRA European dataset [8]), wave height and period (from Copernicus dataset [9]), scatter data, has been gathered from the Italian seas. Both datasets are originally the results of a Reanalysis. The process of reanalysis involves integrating model data with observations to create a comprehensive dataset consistent with the laws of physics. It combines a previous forecast with newly available observations to generate an optimal estimate of the atmosphere's state, termed as analysis, which subsequently leads to an updated and enhanced forecast. From the gathered wind and wave resources data sets were extracted the relative sites scatter dataset which is composed of: mean wind speed at 150 m height form s.w.l.; significant wave height (Hs) and peak wave period (Tp). The analysis encompasses eleven wind design loads scenarios, covering a range of wind speeds from 3 m/s to 23 m/s, with 2 m/s increments and correspondent the wave resource related such as Hs and Tp following the same criteria applied in the work [10]. The Figure 2 shows the yearly gridded mean values of the wind speed (V0) and the significant wave heigh (Hs).



(a) (b)

Figure 2: a) Mean wind speed form CERRA dataset [8] at 100 m from s.w.l; b) Mean significant weave height form Copernicus dataset [9]

The diversification of wind and wave power plays a pivotal role in their combined exploitation. Given the time lag and limited correspondence between these two resources, a hybrid system can effectively mitigate power output variations compared to solely relying on a single resource. To quantify their correspondence, Pearson cross-correlation were computed over the whole gridded dataset across the span time series between the main features of the wind and wave resources as V0 and Hs as done in the papers [11], [12]. The cross-correlation coefficients at $i-th$ grid point ($R_{(p)i}$), is described in Eq. (1):

$$R(p)_i = \frac{1}{N} \sum_{k=1}^{N-p} \frac{|V0_i(k) - \mu_{V0_i}| \times |Hs_i(k-p) - \mu_{Hs_i}|}{\sigma_{V0_i} \sigma_{Hs_i}} \tag{1}$$

where N represents the length of the sample data and p indicates the lag time between mean H_s and $V0$. R(0) denotes the instantaneous cross-correlation between them, with R(p) $=0$ indicating no correspondence and R(p) $=1$ signifying a strong correlation. The μ_{V0_i}, μ_{Hs_i} and σ_{V0_i} and σ_{Hs_i} are the mean value and standard deviation of $V0_i$ and Hs_i time series at i-th grid point. The deployable site was determined by filtering based on bathymetric data. The bathymetry information was extracted from the GEBCO dataset [13] and employed to eliminate areas beyond the depth range of 50 to 200 meters.

2.2. Hybrid concept designs

The Wind and Wave combined hybrid concepts studied involve the combination of two semisubmersible platforms, and a SPAR FOWT platform type [14], [15], along with the point absorbers WEC developed by NREL, specifically the Reference Model 3 (RM3)[16], with its technical features detailed in [17]. The wind turbine under consideration is the reference open-source model IEA Wind 15-MW Turbine [18]. The structural integration between the two power systems was inspired by previous work [19]. The hybrid concepts are illustrated in Figure 3.

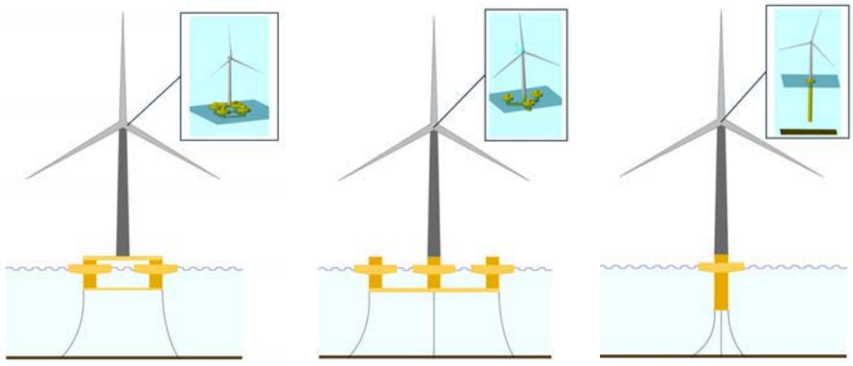

(a) (b) (c)

Figure 3: Illustration of hybrid concepts system: a) $SEMISUB_4$, b) $SEMISUB_3$ and c) $SPAR_1$

- $SEMISUB_4$ The Nautilus platform [15] combined with fours RM3's;
- $SEMISUB_3$ 'The VolturnUs [14] combined with three RM3's;
- $SPAR_1$ [20] and one RM3.

Table 1: Characteristics of hybrid concepts

Feature	$SEMISUB_4$	$SEMISUB_3$	$SPAR_1$	$Units$
Wind turbine				
Hub height	150	150	150	m
Rotor diameter	240	240	240	m
Rated power	15	15	15	MW
Support structure				
Draft	17.05	20	128	m
Platform mass	7.31×10^6	6.74×10^6	1.94×10^7	kg
WEC				
Number of WECs	4	3	1	/
External radius	17.5	17.5	17.5	m
Internal diameter	5.3	5.3	5.3	m
Hull mass	3.84×10^6	3.84×10^6	3.84×10^6	kg
Mooring lines				
Number of lines	4	3	3	/
Chain diameter	0.097	0.33	0.16	m

2.3. TOPSIS analysis

The purpose of this evaluation is to provide a preliminary assessment of the three selected hybrid concepts. By extracting information on existing hybrid concepts, this paper aims to demonstrate a method for identifying and analyzing promising designs. The TOPSIS analysis method is a multi-criteria decision-making technique used to rank alternatives based on their similarity to the ideal solution. The TOPSIS analysis involves several phases (Figure 4): initially, the identification of evaluation criteria is crucial. Criteria are intended as features of the subject investigated. Following this, the criteria are normalized to ensure consistency in their measurement scales, and weights are assigned to prioritize criteria based on their importance. Ideal and negative ideal solutions are then established to represent optimal and suboptimal outcomes for each criterion..

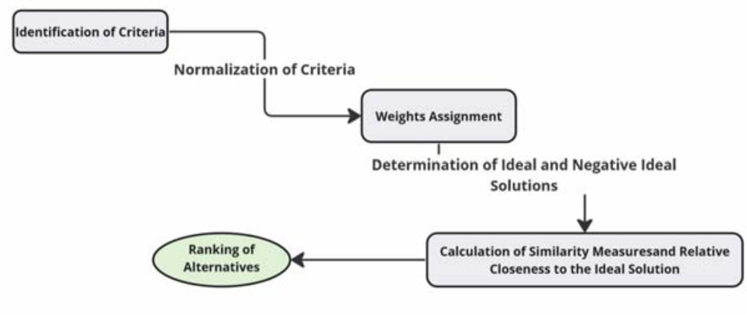


Figure 4: TOPSIS analysis workflow.

Subsequently, similarity measures are calculated to assess the distance between each alternative solution and the ideal and negative ideal solutions. These measures are then used to determine the relative closeness of each alternative to the ideal solution, ultimately resulting in the ranking of alternative solutions based on their suitability for further consideration or implementation. The criteria chosen for evaluating hybrid wind and wave floating offshore systems encompass various aspects: Environmental impact; Social acceptance; Energy production; Dynamic response; Investment cost. As explained in paper [21] it is crucial to assess the weights corresponding to the chosen criteria. The values are typically determined after an interview campaign involving both technical and non-technical groups. In the present paper, the weights were taken as the mean value from previous similar works related to TOPSIS analysis in a similar sector [5], [21]. In Table 2, the weights for each criterion are summarized.

Table 2: Weights of Evaluation Criteria

Attributes	w_i
Environmental Impact	0.6
Social Acceptance	0.5
Extracted Power	0.6
Dynamic Response	0.4
Investment Cost	0.9

Environmental impact criteria consider the environmental impact of the hybrid system. Particularly through a preliminary estimation of CO_2 emissions during the platform production phase. As extracted from the recent form IEA report [22] that direct CO2 emissions due to raw steel production is approximately 1.4 tons CO2 per ton steel produced.

$$CO_2 = mass_{steel}(ton) \times 1.4 \times 10^3 \tag{2}$$

Where for $mass_steel$ we can assume to be the mass of mooring (catenary) the mass that compose the hull of substructure and the WEC mass as following:

$$mass_{steel} = mass_{WEC} + mass_{FOWT} + mass_{mooring} \tag{3}$$

Social acceptance was evaluated preliminary through the analysis of visual impact from the shoreline is a duty to improve the social acceptance for the renewable solution as the offshore marine system. Visual aspects values are evaluated from the following equation, taken from [23]:

$$\begin{aligned} A_{\text{vis}} &= \left(\frac{0.5}{L}\right)^2 \cdot A \qquad \text{for } A_{\text{vis}} < 0.0025\,\text{m}^2 \\ H_{\text{vis}} &= \frac{0.5}{L} \cdot H \qquad\qquad \text{for } H_{\text{vis}} < 0.6\,\text{m} \end{aligned} \tag{4}$$

where A and H represents respectively the surface Area and the heigh of the Offshore hybrid system. Each of the visual aspect index must guarantee to be below the upper limits declared from the regulation [24]. The visual aspect is computed as follows (Eq. 5):

$$V_I = \max(H_{\text{vis}}, A_{\text{vis}}) \tag{5}$$

The 'Economic criteria' is evaluated using a breaking down cost analysis of the main subsystem based on references [5], [25]. The Eq. 6 consider the costs of manufacturing the floating platform (C_{FOWT}) the Costs of the manufacturing of the WEC and the cost of the PTO (C_{WEC}); the costs of wind turbine system (C_{WT}) the cost of the export cable(C_{EC}); and at last the cost of the installation $C_{installation}$).

$$C_{system} = C_{WEC} + C_{FOWT} + C_{WT} + C_{EC} + C_{installation} \tag{6}$$

In the following Table 3, the cost functions are detailed. In Eq. (7), $C_{\text{sp}} = 3$€/kg refers to the cost of steel material. In Eq. (8), the coefficient C_{PTO} depends on the nature of the PTO mechanism of conversion, while the other terms refer to the manufacturing cost to build up the hull of the WEC. In Eq. (9), the cost of the wind turbine depends on the rated generated power (WT_{power}) and a fixed coefficient ($C_{€/\text{kW}} \rightarrow 1200$€/kW). In Eq. (10), L refers to the distance to the shore point approach, and the coefficients f_n are computed considering the form from the paper [26], which depend on the tension (66 kV) and the power to be carried (up to 15 MW), set equal to 1.5.

Table 3: Cost functions of the offshore wind and wave hybrid system.

Equation	**Reference**
$C_{FOWT} = mass_{platform} \times C_{sp}$(7)	[5] [25]
$C_{WEC} = C_{PTO} \times P_{WEC} + C_{sp} \times mass_{WEC}$(8) $C_{\text{PTO}} \rightarrow \begin{cases} 1000\,€/\text{kW} & \text{if Air Turbine} \\ 800\,€/\text{kW} & \text{if Hydraulic} \\ 1400\,€/\text{kW} & \text{if Mechanical} \end{cases}$	[27, 28]
$C_{WT} = C_{e/kW} \times WT_{power}$(9)	[29, 30]
$C_{\text{EC}} = f_n \times 350\,€/\text{m} \times L$(10)	[31, 26]

Regarding the installation cost ($C_{installation}$) it was account As 15% of the total C_{system} value [31].

2.4. Hybrid wind and wave concept dynamic analysis

To capture the dynamic behaviour of the hybrid system, we employed a time-domain analysis. This analysis was conducted using MOST [19], a Matlab-Simscape model capable to handle complex multibody dynamics [22]. The tool enables the preliminary design and analysis of offshore energy as floating foundations and hydrodynamics, wind turbines and aerodynamics, electric generators, and their control algorithms. The numerical simulation was used so to evaluate the criteria of 'Dynamic response' and 'Energy extracted', through the time domain simulation results as done in the paper [32]. The platform's geometries were modelled (based on predefined designs [14], [32, 33] design utilizing the referenced open-source CAD software Salome [34]. Subsequently, with the geometrical and mass properties extracted, it became possible to initiate the BEM solver Nemoh [35], acquiring linear hydrodynamic properties, including added mass, radiation damping, and excitation forces. In the MOST environment, the generation of the wind field is coupled with the executable of Turbsim [36]. The wind field serves as inputs in the simulation of MOST, where the aerodynamics of the wind turbine are obtained based on the theory of the Blade Element Momentum, as explained in the paper [6]. Finally, within the MOST inputs settled, the time-domain analysis was performed to extract power output and pitch inclination over the sea state obtained for each hybrid solution and for each metocean state of the two identified sites.

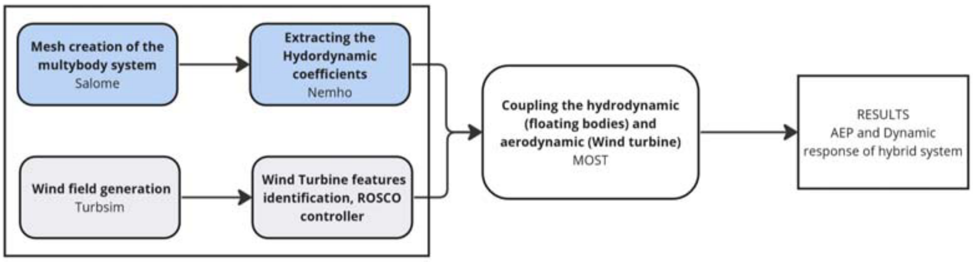


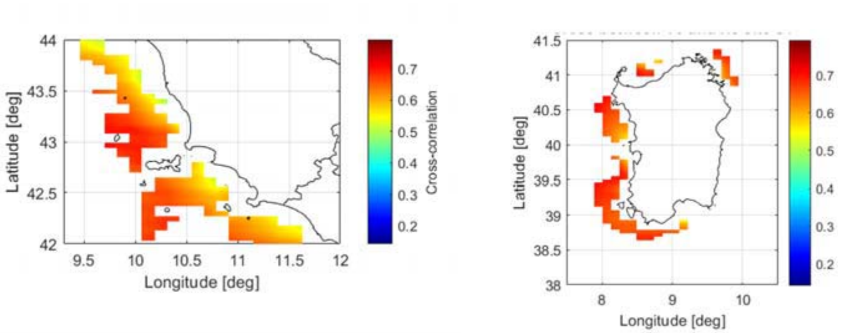
Figure 5: Workflow to perform the time-domain simulating of the hybrid platforms using MOST [7].

3. Results and conclusions

In the following section the main finding of the TOPSIS analysis conducted over the three-hybrid wind and wave concepts applied on an Italian study case. The siting analysis get the results form two promising strategical sites. As illustrated in Figure 6 form the main observation, there were extracted a strategical site to be investigated named as: 'S1' and 'S2'.

In Table 4 the main findings of the resource assessment are summarized, including the mean values of Hs and V0, as well as the Pearson cross-correlation coefficients. The hypothesis of a lag time p equal to 6 hours was applied as similar to the paper [10]. It can be observed that Site S1 has the lowest value of the Pearson cross-correlation coefficient, indicating that it is the site with the most uncorrelated resource.

The following Table 5 resume the results of the attributes for each hybrid platforms at the site S1. As an output of the TOPSIS method, the scores of the alternative platforms



(a) (b)

Figure 6: Italian case study identification, b) S1 and a) S2 sites.

Table 4: Resource analysis results

Site name	Geographical coordinate	V0 (m/s)	Hs (m)	R(p=6)_i
S1	[8.62 38.64]	8	2	0.69
S2	[10.30 42.24]	6	0.8	0.79

are evaluated within the different results obtained from the application at both offshore sites. As shown in Figure 7 for each attribute, we have an ideal solution represented by the red circle and the negative one represented by the blue circle. Therefore, the closer the square point representing the alternative attribute 'score' is to the ideal solution, the higher the score. Conversely, the further away it is, the lower the score.

Table 5: Hybrid Concepts's Criteria values

Criteria	$SEMISUB_4$	$SEMISUB_3$	$SPAR_1$
Environmental impact (CO_2 tons)	35.7	31.22	47.94
Social Acceptance (VI)	0.0092	0.0092	0.0092
Extracted Power (MW)	10.58	11.10	10.70
Dynamic response (inclination in pitch degree)	2.56	1.98	4.70
Investment cost (C_{system} (M€))	87.44	85.47	129.83

The best solution appears to be the alternative $SEMISUB_3$ at Site S1, followed by the alternative $SEMISUB_4$ at Site S1. In the last two positions are the alternative hybrid platforms SPAR at Site S1 and S2. These results reflect two aspects: firstly, the semisubmersible platform performs better compared to the $SPAR_1$ concept, excelling in multiple design aspects such as Economic criteria and stronger dynamic response; secondly, another crucial aspect highlighted by the results is the superior performance at Site S1. Indeed, the resource analysis, it was found to be a more uncorrelated site, allowing for better synergy between both resources.

In conclusion, this research aims to advance sustainable energy solutions, paving the way for the future integration of combined offshore wind and wave energy systems on a commercial scale. A TOPSIS analysis was conducted, facilitating a better understanding of the optimal configuration. This paper seeks to address this gap

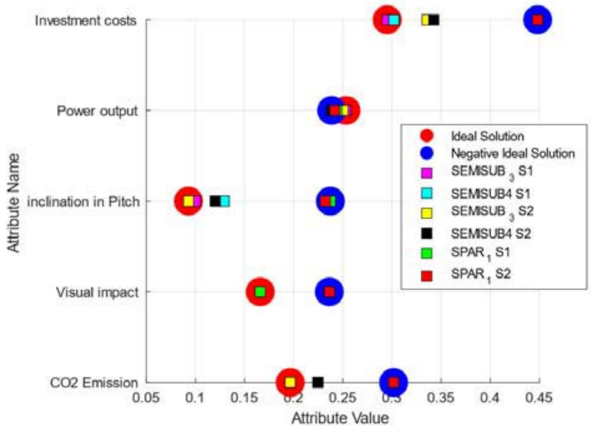


Figure 7: Results from S1 site of the TOPSIS analysis.

by conducting an initial assessment of various concepts, with a specific emphasis on the cutting-edge combinations of platforms and Wave Energy Converters (WECs).

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