Supplementary Information

.1 Onshore prototype

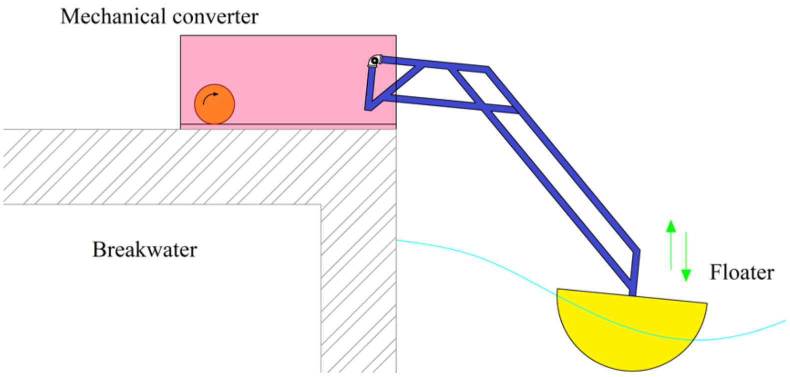


Figure 5: Working principle of the mechanical motion converter.

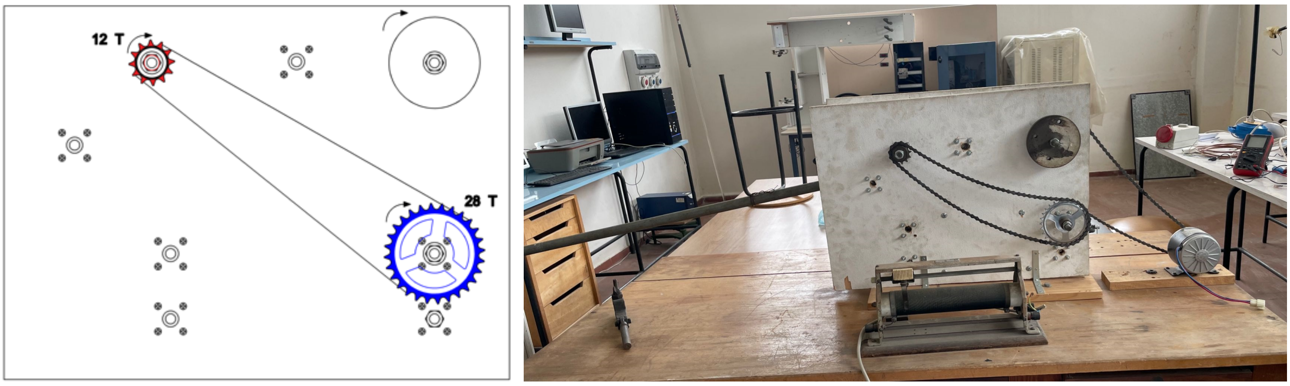


Figure 6: External right-side of the sketch and of the small-scale prototype of mechanical motion converter.

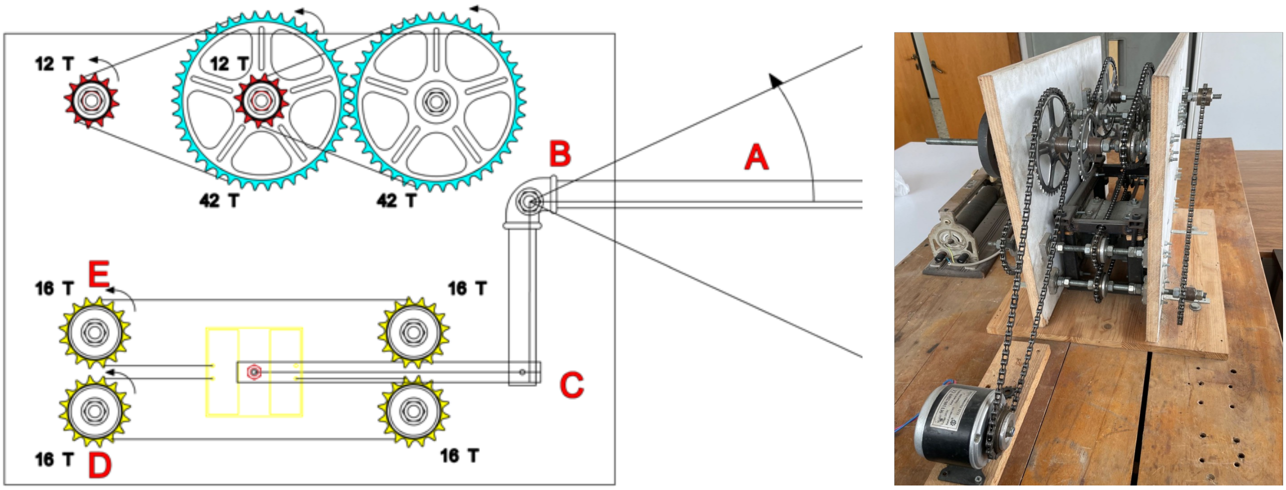


Figure 7: Internal view of the sketch and of the small-scale prototype of mechanical motion converter.

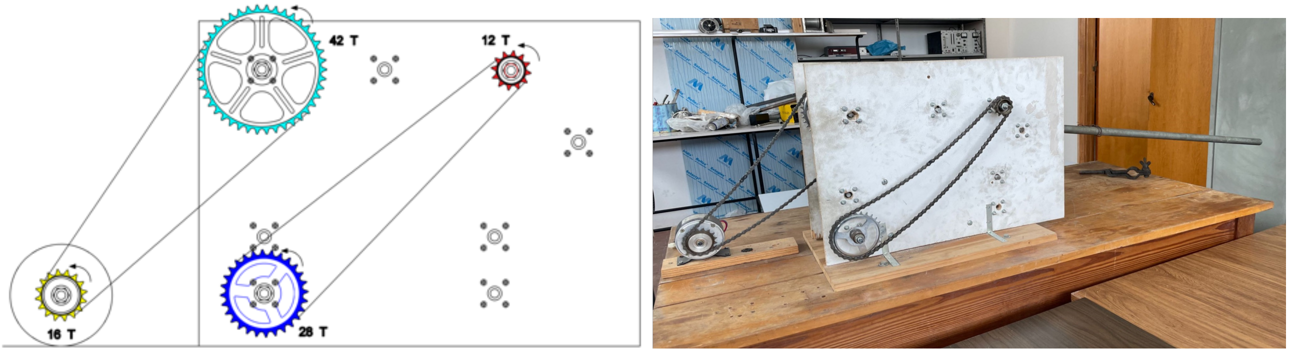


Figure 8: External left-side of the sketch and of the small-scale prototype of mechanical motion converter.

2 Offshore prototype

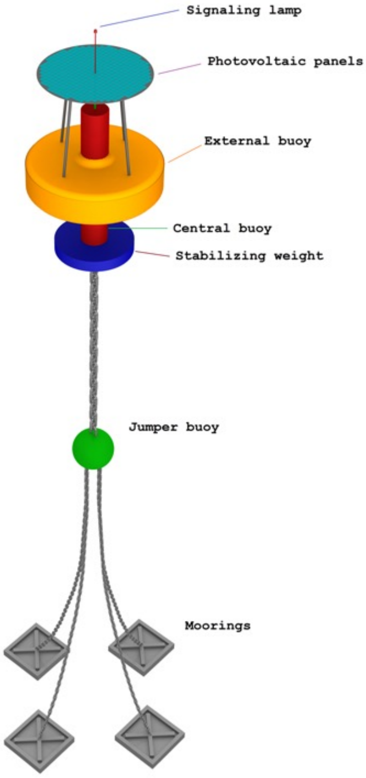
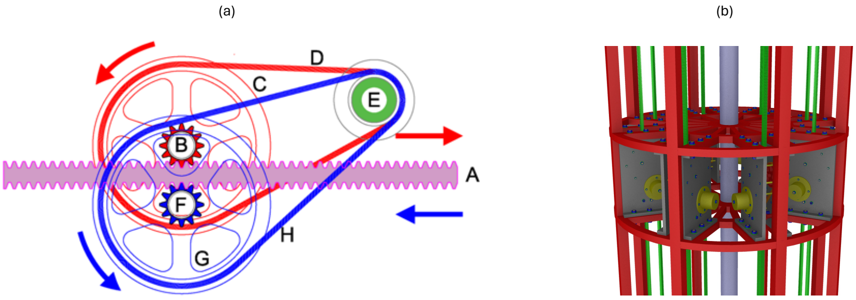


Figure 9: External view of WEC for offshore application.


(a)

(b)

Figure 10: Working principle of the WEC for offshore application.

3 Onshore-nearshore case study

The main features of the wave and wind energy generators used in Eqn. 1 and 2 for the first case study are shown in Table 5. Although these models are manufactured by the same company, the results can be considered generic because wind turbine power output is roughly the same for a given class of turbines, since its main features are stated by the IEC 61400 standards.

Table 5: Rated power and main dimension of the generators employed for the onshore-nearshore case study [50].

Generator	**Rated size [kW]**	**Main dimension**
Wave converter prototype	100	10 m
MHI Vestas V164	10,000	21,124 m^2
MHI Vestas V174	9500	23,779 m^2
Vestas V164	8000	21,124 m^2
Senvion 6.2M126	6150	12,469 m^2
REpower 5M	5075	12,469 m^2
Vestas V90	3000	6362 m^2
Vestas V112	3000	9852 m^2
Vestas V80	2000	5027 m^2

The formula to calculate the minimum feed-in tariff FIT_{min} used for the simulations in the case study 1 is shown in Eq. 4:

$$FIT_{min} = \frac{(C_{inv}\,UCRF + C_{O\&M})\,P}{E}\ , \tag{4}$$

where C_{inv} is the unit investment (or capital) cost [€/kW], $UCRF$ is the Uniform Capital Recovery Factor of the investment [year^{-1}], $C_{O\&M}$ is the unit annual O&M cost [€/(kW year)], P is the rated size of the generator [kW], and E is the annual electricity production. According to Eq. 4, a project is economically doable when the FIT available on the energy market is higher than FIT_{min}, *i.e.* in this case the selected technology gives annual revenue. Differently, the revenue from the electricity production would be lower than the main expected cost items.

The main parameters used to characterize the Vietnamese economic context in Eq. 4 are shown in Table 6, while the average energy potentials from wave and wind in Vietnam coasts are shown in Figure 11 and Figure 12, respectively [30].

Table 6: Main parameters used for the economic analysis in the onshore case study [34, 51].

Parameter	**Value**
Wave converter unit investment cost	3500 USD/kW
Offshore wind turbine unit investment cost	2870 USD/kW
Wave converter O&M unit cost	35 USD/(kW y)
Offshore wind turbine O&M unit cost	158 USD/(kW y)
Wave converter technical life	25 years
Offshore wind turbine technical life	30 years
Real interest rate	3.998

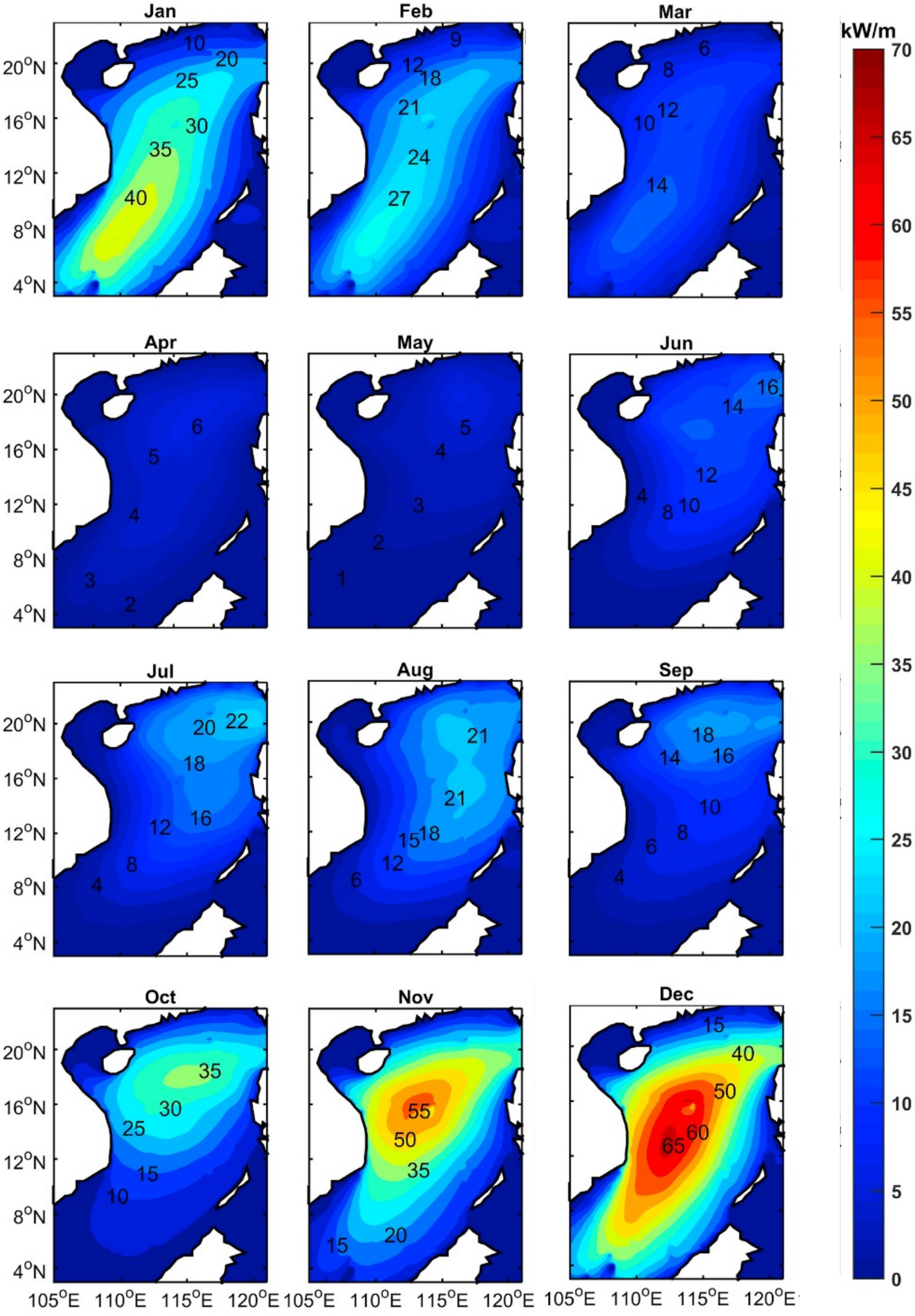


Figure 11: Spatial patterns of the monthly averaged wave energy potential from December to November [kW/m].

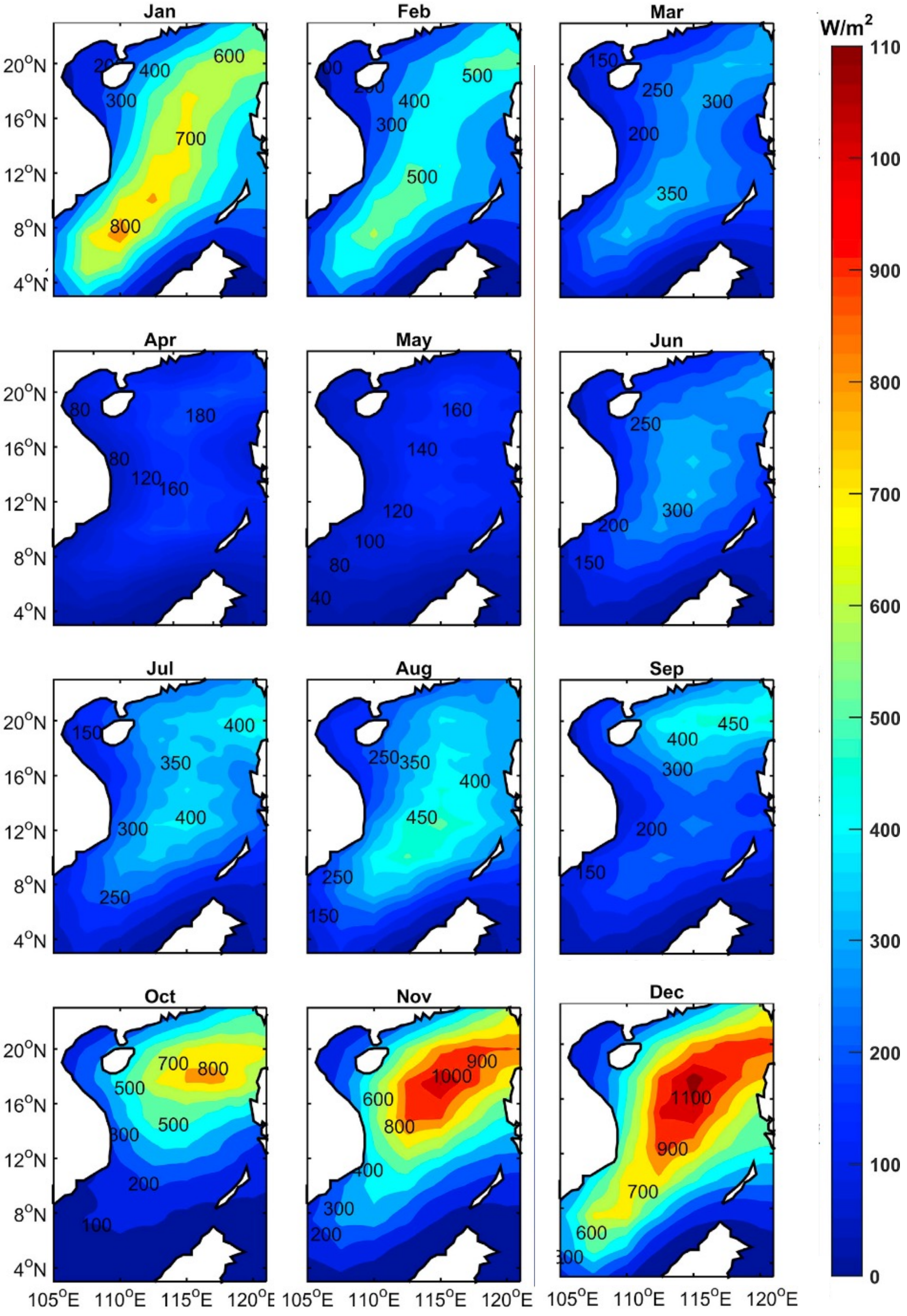


Figure 12: Spatial patterns of the monthly averaged wind power density from December to November [W/m²].

4 Offshore case study

For the solution of this case study, the terms in Eq. 3 were expressed employing the costs for the initial investment ($c_{inv,SW}$, $c_{inv,PV}$, and $c_{inv,WT}$) and the annual O&M costs ($c_{O\&M,SW}$, $c_{O\&M,PV}$, and $c_{O\&M,WT}$) per unit power, as well as expressing the electricity production from each source, as shown in Eqn. 5, 6, and 7. The total rated power from each source is expressed through the parameters P_{SW}, P_{PV}, and P_{WT} for sea wave converters, photovoltaic modules, and wind turbines, respectively.

$$\sum C_{inv,t} = c_{inv,SW}\ UCRF_{SW}\ P_{SW} + c_{inv,PV}\ UCRF_{PV}\ P_{PV} + c_{inv,WT}\ UCRF_{WT}\ P_{WT}\ , \tag{5}$$

$$\sum C_{O\&M,t} = c_{O\&M,SW}\ P_{SW} + c_{O\&M,PV}\ P_{PV} + c_{O\&M,WT}\ P_{WT}\ . \tag{6}$$

$$\sum E_t = E_{SW} + E_{PV} + E_{WT}\ . \tag{7}$$

Furthermore, considering a unique size value for each RES technology, the cumulated installed power can be expressed as the product of the rated power ($P_{SW,rated}$, $P_{PV,rated}$, and $P_{WT,rated}$) times the number of devices of each technology (n_{SW}, n_{PV}, and n_{WT}), as in Eqn. 8:

$$\begin{cases} P_{SW} = n_{SW}\ P_{SW,rated} \\ P_{PV} = n_{PV}\ P_{PV,rated} \\ P_{WT} = n_{WT}\ P_{WT,rated}\ . \end{cases} \tag{8}$$

The same approach can be applied to the electricity output, evaluating the production from each source as the product between the number of devices and the electricity output of a single device for each technology.

The last missing terms to solve Eq. 3 are the annual electricity production from each RES technology. Since this is an energy planning study, a more detailed approach was applied, with respect to the first case study.

About sea waves, to evaluate the electricity output of a single converter, Eq. 1 was further detailed describing the average wave energy flux through the significant height H_s and the energy period T_e of waves, assuming to be in deep water conditions [52]. Both parameters were calculated from the spectrum analysis of the measured waves [53, 54], as in Eq. 9.

$$E_{SW} = w_{SW}\ \bar{\eta}_{SW}\ \frac{\rho_{SW}\ g^2}{64\ \pi} \sum_{j=1}^{12} H_{s,j}^2\ T_{e,j}\ \Delta t_j\ , \tag{9}$$

where $\rho_{SW} = 1025$ kg/m^3 is the seawater density, $g = 9.81$ m/s^2 is the gravity acceleration, and Δt_j represents the number of hours in each month.

The electricity production from photovoltaic modules was evaluated according to Eq. 10, where S_{PV} is the surface of the photovoltaic modules, $\bar{\eta}_{PV}$ is the average value of its efficiency, and $H_{d,j}$ is the monthly average value of the daily solar radiation [55].

$$E_{PV} = S_{PV}\ \bar{\eta}_{PV} \sum_{j=1}^{12} H_{d,j}\ \Delta t_j\ . \tag{10}$$

Wind potential is often modeled through a statistical distribution function based on measurements that are extended to the whole operating life of the system. This kind of expression represents the probability that a specific value of wind speed v occurs during the measuring period, like a year or a month [54]. Although the Weibull distribution is the most reliable and employed function for wind speed statistical analysis [56], the IEC 61400-1 standard [57] suggests the adoption of a Rayleigh distribution (Eq. 11) for a preliminary energy evaluation, that can be derived from the Weibull distribution setting the shape parameter equal to 2.

$$f_R(v) = \frac{2\ v}{\lambda^2}\ exp\left[-\left(\frac{v}{\lambda}\right)^2\right]\ . \tag{11}$$

where λ is the scale factor [58]. The average wind speed $\langle v \rangle$, which is frequently available in the literature [59], is defined as the first-order moment of the probability density function, as in Eq. 12:

$$\langle v \rangle = \int f_R(v)\ v\ dv = \frac{\sqrt{\pi}}{2}\ \lambda\ . \tag{12}$$

Furthermore, it is necessary to correct the wind speed measured values since this quantity depends on the altitude, converting the measures to the hub height of the selected wind turbine model. This operation is usually performed in the literature using a power law or a logarithm law converting the values measured at a reference quote z_r (usually 10 m) to the height z where the wind turbine hub [57], introducing constant terms to take

Table 7: Main features of the wind turbine selected for the offshore case study [62].

Parameter	**Value**
Model	Vestas V117
Rated power	4,200 kW
Rotor diameter	117.0 m
Hub height	91.5 m
Cut-in speed	3.0 m/s
Nominal speed	12.0 m/s
Cut-off speed	25.0 m/s

Table 8: Main parameters for the offshore case study [34, 51, 63].

Quantity	**Wind energy**	**Solar energy**	**Wave energy**
Investment cost [$/kW]	2870	1980	3348
O&M cost [$/kW]	158	18	35
Rated power [kW]	5000	10.8	80
Useful life [years]	30	20	25
UCRF [-]	0.058	0.074	0.064

into account the orography of the territory [60]. For the present study, the logarithmic law shown in Eq. 13 was employed, using the coefficient z_0 = 0.0002 m related to open sea conditions.

$$\langle v \rangle_z = \langle v \rangle_r \, \frac{ln\left(\frac{z}{z_0}\right)}{ln\left(\frac{z_r}{z_0}\right)} \; . \tag{13}$$

The set of Eqn. 11 – 13 allow converting the average wind speed into the wind speed distribution function. To assess the average electricity production of a single wind turbine, in lieu of Eq. 2, the power curve usually available on manufacturers' datasheets was utilized, according to Eq. 14, where Δt_j is the time horizon over which the Rayleigh distribution is evaluated, and $\psi\ (v)$ is the function giving the power output of the wind turbine. Although wind turbines electricity production directly depends on air density [61], a constant value related to the standard conditions was utilized in this study.

$$E_{WT} = \sum_{j=1}^{12} \Delta t_j \int f_{R,j}(v)\ \psi(v)\ dv \; . \tag{14}$$

A commercial turbine was selected to evaluate the offshore wind power, having the main features reported in Table 7 [62]. The other parameters used for the present case study are shown in Table 8.

The optimization algorithm illustrated in Eqn. 3, 5 – 14 was solved with the following additional conditions (constraints):

- Since wind turbines can be installed on two different points, the number of wind turbines is given by $n_{SW} = n_A + n_B$;
- Since the photovoltaic modules are integrated into the WEC systems, $n_{SW} = n_{PV} = n_C$.

Furthermore, the variables were subject to the following additional constraints already explained in the main text of the paper:

$$\begin{cases} n_A,\ n_B,\ n_C \ are\ integer \\ \alpha - toll \leq \frac{E_{WT}\ +\ E_{SW}\ +\ E_{PV}}{E_d} \leq \alpha + toll \\ E_{WT,j}\ +\ E_{SW,j}\ +\ E_{PV}, j \leq E_{d,j} \\ \frac{E_{SW}\ +\ E_{PV}}{E_{WT}\ +\ E_{SW}\ +\ E_{PV}} \geq \beta \end{cases} \tag{15}$$

5 Discussion

The simulations described in the present paper suggest that wave energy, as well as offshore wind energy, can be abundant in selected locations in Vietnam but it is not economically profitable to invest in these technologies with the current FIT. Since some offshore wind farms are already in operation or in construction phase in this country, the Authors investigated the available literature on these projects to validate the results of the present paper. Data were gathered on four projects, with two out of four being terminated when the available

FIT was equal to 7.80 cUSD/kWh [64] while the latter were announced after the issue of Decision n. 39 (FIT equal to 9.80 cUSD/kWh) [65]. Investigation on the investments occurred in previous years shows that, even with a lower FIT, investments were more profitable, while the inflation made non-attractive the higher FIT, as shown in Table 9. Since the declared performance of the two operating projects appear as optimistic, two additional scenarios were investigated, hypothesizing realistically 3000 and 3500 equivalent operating hours [66]. It is possible to see that the two operating projects with the declared performance were highly attractive, with a Pay-back Period lower than 9 years. In the Simulation scenario 1, only one project has a Pay-back Period higher than 10.5 years, while in Simulation scenario 2 two investments out of four still show good values of Pay-back Period (lower than 10.5). These economic performance somehow confirm the poor results obtained in the present paper, since the potential profit is low and also subject to the uncertainties related to the wind energy availability, although Vietnam has a good wind potential.

Table 9: Economic feasibility of actual projects in offshore wind energy in Vietnam.

WIND FARM	**PhuQuy**	**Bac Lieu**	**PV Power - IMPSA**	**PhuCuong**
Year	2012	2016	*n.a.*	2020
Rated power *[MW]*	6	99.2	600	600
Investment cost *[MUSD]*	14.27	222.26	2350	2000
Unit investment *[USD/kW]*	2378.7	2240.5	3916.7	3333.3
DECLARED PERFORMANCE				
Equivalent hours *[h/year]*	4,200	3,225.81	*n.a.*	*n.a.*
Electricity production *[MWh]*	25,200	320,000	*n.a.*	*n.a.*
Revenue *[MUSD/year]*	1.97	24.96	*n.a.*	*n.a.*
Pay-back Period *[years]*	7.26	8.90	*n.a.*	*n.a.*
SIMULATION 1: 3500 equivalent hours				
Equivalent hours *[h/year]*	3500	3500	3500	3500
Electricity production *[MWh]*	21,000	347,200	2,100,000	2,100,000
Revenue *[MUSD/year]*	1.6	27.1	205.8	205.8
Pay-back Period *[years]*	**8.71**	**8.21**	**11.42**	**9.72**
SIMULATION 2: 3000 equivalent hours				
Equivalent hours *[h/year]*	3000	3000	3000	3000
Electricity production *[MWh]*	18,000	297,600	1,800,000	1,800,000
Revenue *[MUSD/year]*	1.4	23.2	176.4	176.4
Pay-back Period *[years]*	**10.17**	**9.57**	**13.32**	**11.34**

References

[50] Lucas Bauer and Silvio Matysik. Wind turbine models web page. https://en.wind-turbine-models.com/, 2024. Accessed: 2024-03-25.

[51] Worldbank. Vietnam real interest rate. https://data.worldbank.org/indicator/FR.INR.RINR?locations=VN, 2024. Accessed: 2024-04-29.

[52] D. Vicinanza, P. Contestabile, and V. Ferrante. Wave energy potential in the north-west of Sardinia (Italy). *Renewable Energy*, 50:506–521, 2013. ISSN 09601481. doi: 10.1016/j.renene.2012.07.015.

[53] B.G. Reguero, I.J. Losada, and F.J. Méndez. A global wave power resource and its seasonal, interannual and long-term variability. *Applied Energy*, 148:366–380, 2015. ISSN 03062619. doi: 10.1016/j.apenergy.2015.03.114.

[54] George Emmanouil, George Galanis, Christina Kalogeri, George Zodiatis, and George Kallos. 10-year high resolution study of wind, sea waves and wave energy assessment in the greek offshore areas. *Renewable Energy*, 90:399–419, 2016. ISSN 18790682. doi: 10.1016/j.renene.2016.01.031.

[55] Yinyin Fu, Xin Liu, and Zengwei Yuan. Life-cycle assessment of multi-crystalline photovoltaic (pv) systems in china. *Journal of Cleaner Production*, 86:180–190, 2015. ISSN 09596526. doi: 10.1016/j.jclepro.2014.07.057.

[56] Saiyad S Kutty, M G M Khan, and M Rafiudin Ahmed. Wind energy resource assessment for Suva, Fiji, with accurate Weibull parameters. *Energy Exploration & Exploitation*, 37(3), 2019. doi: 10.1177/0144598719842379.

[57] International Electrotechnical Commission (IEC). IEC 61400-1. Wind energy generation systems. Part 1: Design requirements, 2019.

[58] Geovanni Hernández Galvez, Ricardo Saldaña Flores, Ubaldo Miranda Miranda, Omar Sarracino Martínez, Margarita Castillo Téllez, Damianys Almenares López, and Anahí Karina Tapia Gómez. Wind resource assessment and sensitivity analysis of the levelised cost of energy. A case study in Tabasco, Mexico. *Renewable Energy Focus*, 29(June):94–106, 2019. ISSN 17550084. doi: 10.1016/j.ref.2019.03.001.

[59] M. Majidi Nezhad, D. Groppi, P. Marzialetti, L. Fusilli, G. Laneve, F. Cumo, and D. Astiaso Garcia. Wind energy potential analysis using Sentinel-1 satellite: A review and a case study on Mediterranean islands. *Renewable and Sustainable Energy Reviews*, 109(December 2018):499–513, 2019. ISSN 18790690. doi: 10.1016/j.rser.2019.04.059.

[60] Simona Culotta, Vincenzo Franzitta, Daniele Milone, and Gino Giudice. Small wind technology diffusion in suburban areas of sicily. *Sustainability*, 7(9):12693–12708, september 2015. ISSN 2071-1050. doi: 10.3390/su70912693.

[61] Giuseppina Ciulla, Vincenzo Di Dio, Diego La Cascia, Valerio Lo Brano, and Francesco Montana. Effects of the air density value on a wind generator electricity production capability. *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, page 1–6, 2016. doi: 10.1109/EEEIC.2016.7555512.

[62] Vestas. 4 MW Wind Turbines Datasheet. `https://puc.sd.gov/commission/dockets/electric/2018/EL18-003/testimony/testimony/kaaz/4_MW_Product_Brochure.pdf`, 2024. Accessed: 2024-11-06.

[63] Vincenzo Franzitta, Domenico Curto, and Davide Rao. Energetic Sustainability Using Renewable Energies in the Mediterranean Sea. *Sustainability*, 8(11), 2016. ISSN 2071-1050. doi: 10.3390/su8111164.

[64] The Vietnamese Prime Minister. Decision no. 37/2011/qd-ttg of the prime minister on the mechanism supporting the development of wind power project in vietnam, 2011. URL `https://policy.asiapacificenergy.org/sites/default/files/110629.37_2011_QD-TTg.En_.pdf`. Accessed: 2024-11-06.

[65] The Vietnamese Prime Minister. Decision no. 39/2018/qd-ttg dated september 10, 2018 amending and supplementing a number of articles of decision 37/2011/qd-ttg dated june 29, 2011 by the prime minister on supporting mechanism to develop wind power projects in vietnam, 2018. URL `https://vepg.vn/wp-content/uploads/2018/10/39_2018_QD-TTg_1009188_CP_New-Wind-FIT_Unofficial-EN-Transl.pdf`. Accessed: 2024-11-06.

[66] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2022, 2023.