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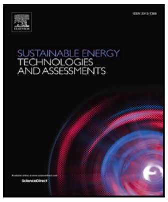

Original article

Wave energy systems in the Vietnamese context: Proposal for onshore and offshore integration based on a techno-economic analysis

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ABSTRACT

Renewable energy introduction is one of the main goals for the evolution of the power system in the 21st century. The most popular technologies are based on photovoltaic panels or wind turbines, but other energy sources such as sea waves energy should be also exploited. Moreover, although a great effort has already been spent in developed countries, pushing the investments through economic subsidies, many developing countries are lagging, still basing most of their power generation-mix on fossil fuels. In this study, two prototypes for sea wave energy exploitation are illustrated, one for onshore and one for offshore application. To demonstrate their feasibility, a techno-economic analysis for their introduction in Vietnam is provided, comparing their performance with more mature technologies such as wind and solar. Results show that, with adequate economic conditions, this technology might be a good support to the decarbonization of the energy system. Regarding the renewables policy, Vietnamese government should support these renewable energies with a higher feed-in tariff to make the investments profitable. Nevertheless, with reference to the offshore technology, a renewable mix based on this energy converter was proved to be economically viable, with LCOE between 6.45 and 6.56 cUSD/kWh and NPV between 4,500 and 51,700 kUSD over 20 years.

Introduction

Motivation

Renewable Energy Sources (RES) have gained substantial traction in recent decades as the future energy production technologies. Their primary objective is mitigating global warming and environmental pollution from fossil fuels while also postponing the risk of resource depletion. However, the transition away from fossil fuel power plants faces hurdles amid the relentless surge in global final energy demand, primarily due to the development of many countries in Asia [1].

In 2021, fossil sources (coal, oil, and natural gas) still constituted the 79% of total energy supply, with renewables meeting only 13% of demand [2]. Achieving a more sustainable society demands great efforts worldwide, especially if countries intend to achieve the Near Zero Emission scenario by 2050.

Commercially mature technologies in the RES field are available, like wind turbines, hydro turbines, photovoltaic panels (PV), and steam turbines for geothermal applications [3–5]. However, their deployment varies due to regional disparities in primary energy sources and concerns over land use and visual impact to preserve the landscape. For these reasons, further RES such as ocean energy should be also exploited [6], particularly for small islands [7–11] and coastal nations [12] where the potential to satisfy energy demands is favorable. The seas and oceans present vast energy buffers due to waves, currents, tides, water temperature differences, and salinity gradients [13–15].

Nevertheless, the development of sea energies and especially wave energy had limited success so far mainly due to the frequent extreme meteorological conditions in the areas with remarkable wave energy potential [16]. Although numerous concepts and prototypes have been proposed in the past [17], only few have progressed to the testing phase and there are currently no commercially available devices [18].

Contribution

In recent years, University of Palermo researchers have focused on creating innovative devices for the utilization of sea wave energy in onshore and offshore locations. These systems employ mechanical converters to turn vertical oscillations caused by waves into a mono-direction rotary motion, powering commercial electrical generators akin to those available in small wind turbines.

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Two prototype concepts are described, the first for onshore [19] and the second for offshore application [20], respectively. To give some indication about the economic sustainability of these prototypes, an energy and economic analysis of their installation in the context of Vietnam, a country with large coastlines, is provided. The Vietnamese sea energy potential was deeply reviewed in a previous publication by the authors [21], showing the high attractiveness of this RES. Nevertheless, the national government has never promoted investments in this energy source. In detail, the Vietnamese power system has been based on Feed-In-Tariffs (FIT) for RES technologies for many years, while currently the regulations on FIT prices for renewable energy have expired. Vietnam has subsequently issued The Power Development Plan for the 2021–2030 period, with a vision to 2050, so that new projects are waiting for instructions on the auction mechanism, bidding to select the investor with electricity price from the government.

The main contribution of the present paper is a sustainability analysis based on energy production (social dimension), avoided carbon emissions (environmental dimension) and the main synthetic indicators for investments evaluation (economic dimension) resulting from the installation of two different wave energy prototypes. The analysis was based on two specific case studies developed in the Vietnamese context. Furthermore, the performance of the two prototypes were compared with the wind energy, a much more mature RES technology that was remunerated in the past by the Vietnamese government. In detail, the Levelized Cost Of Energy (LCOE) was calculated in both cases, assessing the values in selected points for the onshore technology and minimizing the value related to an optimal RES mix in the latter case study. Furthermore, a deep economic analysis based on the most used indicators was performed on this second case. For both scenarios, the energy production and the carbon emissions reduction were assessed. Although the authors evaluated the performance of these energy converters in a specific context, the methodology illustrated is generic and can be extended to any location using site-specific data on the average availability of renewable energies.

The paper is structured as follows: Section “WEC concepts and techno-economic analysis” illustrates two Wave Energy Converter (WEC) prototypes and the methods used in this study to evaluate the economic feasibility of their installation. In Section “Case Studies”, a review of wave energy potential in Vietnam is provided and the two case studies considered for the analysis are described. Section “Results” shows the main results of this study, while Section “Conclusions” provides a discussion of the results obtained and the conclusions of the article.

WEC concepts and techno-economic analysis

WEC concepts

To exploit energy from sea waves, two different technologies are illustrated in the present paper. Both systems are being developed at the University of Palermo. With respect to the other technologies illustrated in existing literature [18,22], both of the proposed technologies have the following positive features:

- No pressurized fluids are necessary;
- The designs consist in a limited number of parts;
- The exploitation of commercial components minimizes the costs for research and development;
- The investment costs are limited due to common materials drawn from other industrial sectors.

In contrast, the proposed technology concepts have the following disadvantages with respect to more mature technologies and other RES:

- Costs for energy production could be higher;
- A part of the mechanical energy input is dissipated inside the converter;
- The output axis is affected by a pulsating unidirectional rotary motion, due to the natural oscillation of waves and the rectification of the mechanical motion.

Onshore prototype

The proposed device aims to exploit sea wave energy near coastlines by installing a mechanical motion converter directly on the existing breakwaters close to harbors, recovering wave energy rather than simply dissipating this source on the infrastructure.

The main working principle of the device for onshore application is depicted in Figure 5 in the Appendix A of this paper. A floater is connected by a bar to a hinge, fixed to the mechanical motion converter on the breakwater. The unique degree of freedom of the bar is the rotation around the hinge. According to the sea wave motion, an alternative rotation is applied to the mechanical motion converter.

Inside, a combination of freewheels and chains is used to rectify the rotation and produce a unidirectional rotary motion to activate an alternator. The small-scale prototype is designed to exploit a vertical oscillation up to 0.95 m, since the bar is 1.13 m long, and it can oscillate 25° upward and 25° downward. Both the sketch of the converter and the pictures of the current version of small-scale prototype are provided in Figure 6 - 8, respectively. With specific reference to Figure 7, the movement of a floater generates the rotation of the input bar (A) around the hinge (B) and consequently a translation of the slider (C). This component is connected to the freewheels (D and E) by chains to transfer the rotational motion only in the desired direction. The chains around D and E are mounted in a symmetrical way to exploit the mechanical energy input from both the directions of the slider.

Externally, the rotations from the axes of freewheels D and E are connected to the same output axis. As shown in Figure 6 and 8, additional axes are installed to increase the rotational speed up to the rated value of the electrical generator.

Finally, a freewheel, as depicted in Figure 8, is added to the final axis before the electrical generator. This addition allows the electrical machine to be disconnected if the mechanical motion converter’s angular speed drops below the generator’s instantaneous value. This ensures a more regular production of electrical energy.

The current version of the prototype is equipped with a 24 V DC generator installed at the output axis and connected to a rheostat.

An analytical analysis of the electrical power output and first laboratory tests over this prototype were published in [23–26].

Offshore prototype

As well known, the sea wave energy potential is higher and more regular in offshore areas than in nearshore locations [18]. An innovative WEC for the exploitation of this RES, which is currently still in a development phase, is shown in Figure 9 in Appendix B. Since the device must be installed in an offshore area, this WEC is equipped with a mooring system, composed of chains, anchors, and a jumper buoy.

The wave energy extraction relies on two coaxial cylindrical floaters. Each buoy has a different purpose: the outer buoy moves vertically, following the wave crest, while the inner buoy is almost firm. A stabilizing weight attached to the lower part of the inner buoy minimizes vertical oscillation through inertia and hydrodynamic resistance. Due to their different behaviors to the sea wave, a relative motion is produced between the two buoys.

This motion drives mechanical motion converters within the inner buoy. A modular approach improves device reliability and modulates hydrodynamic reaction based on wave energy availability. The system houses eight converters, for a total rated power of 80 kW. Like the onshore solution, this WEC is designed to utilizes commercial generators to minimize component costs. An electronic power converter links the device to the grid, ensuring power quality to comply with grid requirements [27]. Figure 10(a), situated in Appendix B, illustrates the working principle of the mechanical motion converters inside the inner buoy.

The relative motion between the two floaters (vertical movement in the device, horizontal in the picture) is transferred inside the central buoy, by using a bifacial rack (A). Both sides are connected by freewheels (B and F) and belts (D and H) to the same output axis (E). Each side is mechanically activated, according to the direction of the motion of the bifacial rack. Thus, the working principle is similar to the one described in the previous section. As stated above, eight motion converters are installed inside the central buoy. A possible configuration is shown in Figure 10(b) in Appendix B.

To further increase the electrical output, the offshore WEC can also incorporate a PV module on the top of the outer buoy. Additionally, this kind of device might also be used as a marker buoy delineating reserved areas, making it attractive for protected zones like small islands. This device has currently undergone some testing, evaluating its performance via simulations and laboratory experiments [19,20,28].

Techno-economic analysis

The techno-economic analysis described in this paper was performed using technical parameters, such as the average energy efficiency of the converters and the average renewable energy availability, and economic parameters, such as the average investment and O&M costs for the commercially available wave energy converters. Although the feasibility is valuated in specific locations, the method adopted in this study can be easily extended to any onshore and offshore location. As a limitation of the study, it is worth to highlight that the analysis was based on energy conversion without assessing the performance of power electronics [29].

Onshore-nearshore case study

The monthly average potential electricity production E from the sea wave converter (subscript SW) and from wind turbines (subscript WT) can be assessed according to Eq. (1) and (2), respectively:

$$E_{SW} = w_{SW}\ \bar{\eta}_{SW} \sum_{i=1}^{12} e_{SW,i}\ N_i\ , \tag{1}$$

$$E_{WT} = S_{WT}\ \bar{\eta}_{WT} \sum_{j=1}^{12} e_{WT,j}\ N_j\ , \tag{2}$$

where w_{SW} is the wave energy converter width, S_{WT} is the wind turbine swept area, $\bar{\eta}$ is the average efficiency of the converter, e is the average exploitable energy potential in the ith month, and N is the number of hours in the ith month. The energy production evaluation was performed using monthly average wave and wind power potentials gathered from [30]. These values, based on a 30-year assessment, are illustrated in Appendix C in Figure 11 and Figure 12, respectively.

The economic feasibility of the installation of the WEC and wind turbines was assessed evaluating the LCOE, *i.e.* the minimum value of the remuneration for the electricity sold to the grid able to balance the outgoings over the lifetime of the technology. The generic mathematical formula of the LCOE is shown in Eq. (3):

$$LCOE = \frac{\sum_{t=1}^{T} \left(C_{inv,t} + C_{O\&M,t} + C_{Fuel,t} + C_{Decom,t}\right)(1+r)^{-t}}{\sum_{t=1}^{T} E_t (1+r)^{-t}}\ , \tag{3}$$

where $C_{inv,t}$ is the capital investment cost, including costs for the purchase of the equipment as well as for grid expansion, transformer and power converters, $C_{O\&M,t}$ is the Operation and Maintenance cost, $C_{Fuel,t}$ is the cost related to the purchase of the fuel (equal to zero for wave and wind energies), $C_{Decom,t}$ is the cost for the decommissioning of the plant at the end-of-life, E_t is the electricity production, and r is the real interest rate. All these terms are referred to the year t and should be summed up to the technical life T. In this study, since the onshore WEC is still in developing phase, the authors were able to estimate the first two cost terms (capital investment and O&M) based on average literature values, neglecting decommissioning costs. Furthermore, the analysis was performed over a standard year, using a constant annual value for $C_{O\&M,t}$ and annualizing the capital cost through the Uniform Capital Recovery Factor (UCRF) of the investment [31]. Both cost terms were referred to the unit rated power. This quantity would be thus the minimum hypothetical FIT to provide to the owner of the plant to make the investment profitable.

Since wave energy exploitation has no FIT available in Vietnam, the methodology here proposed is used to calculate a minimum FIT for WEC and offshore wind turbines, proposing a reference value for the former and comparing the results with the current FIT for the latter.

The complete mathematical model developed for this case study is illustrated in Appendix C.

Offshore case study

For the second case study, since the offshore energy potential is higher and much more economically feasible than onshore, a different approach was adopted, although it is also based on the LCOE evaluation. In detail, to identify the best economically feasible RES mix, a simplified mathematical model solved through an optimization algorithm was developed for the study. The optimization allows for supplying a fixed share of the local energy demand identifying the best RES mix [21] according to the minimization of the LCOE of the entire proposed renewable mix system [32] rather than on the LCOE of a single technology. Even in this case study an annual evaluation was performed, thus simplifying the Eq. (3) without summing over the lifetime of the investment but performing a summation over the technologies and annualizing investments using the UCRF related to each technology.

For each renewable technology (sea wave, wind, and PV), investment and O&M unit costs are usually available in the literature [33,34]. Nevertheless, since the sea wave converter assessed in this study is a prototypical device, data from a previous study of some of the Authors was used as a Ref. [35].

The decision variables of the optimization problem are the number of devices for each technology to be installed. The objective function, *i.e.* the target of the optimization, is the minimum LCOE of the entire energy mix, according to Eq. (3), corresponding to the desired share of RES energy production.

Further constraints of the problem were also introduced, expressing the following conditions:

- The number of devices for each technology must be an integer value;
- The annual RES production to achieve is α fraction of the energy demand E_d; this value was varied with a step of 5%;
- Since the number of devices is discretized, to identify a solution a tolerance $toll = \pm 0.3\%$ was introduced;
- In each month, the renewable mix production must not be higher than the monthly energy demand $E_{d,j}$;
- To ensure a minimum installation of WEC + PV, the electricity produced from these technologies must have a RES share higher than or equal to $\beta = 2\%$, despite the higher costs. This additional constraint was included to force the algorithm to identify a sub-optimal solution involving the WEC technology.

The complete mathematical model developed for this case study is illustrated in Appendix D.

Case studies

Wave energy potential in Vietnam

Only a limited number of studies investigating the Vietnamese wave potential is available in the international literature. In 2010, a research project assessing all the forms of sea energy (waves, tides, and offshore wind) was supported by the Government; nevertheless, this research did not have any follow-up [36,37]. In 2014, Ly et al. [38] focused

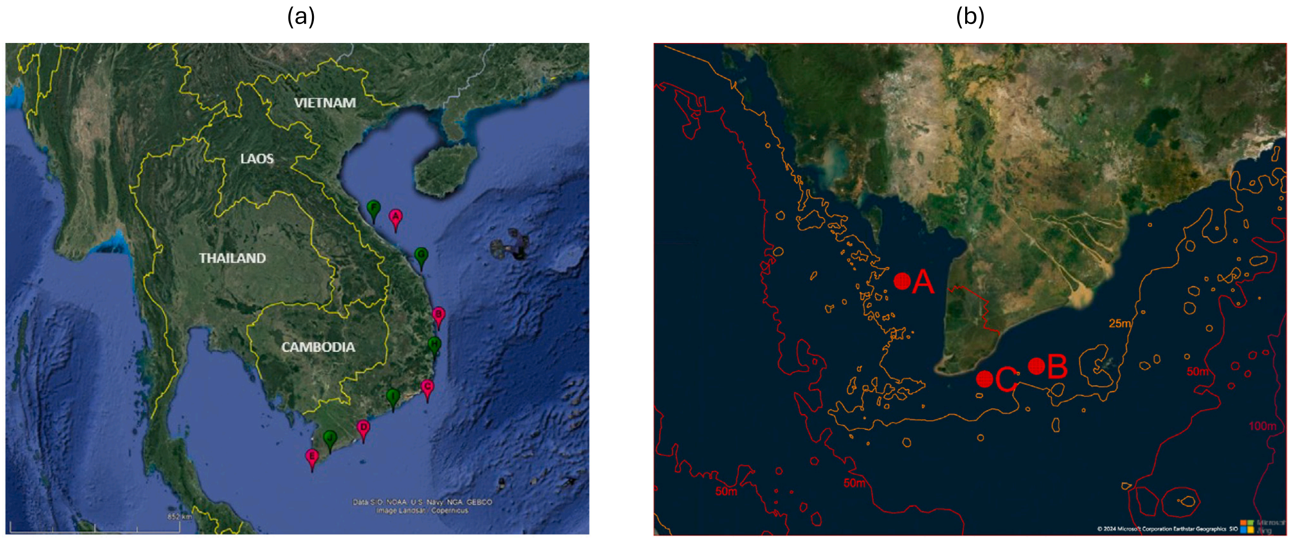


Fig. 1. Installation points for the onshore sea waves (green) and wind (red) energy generators for the onshore case study (a); installation points for the energy generators for the offshore case study (b).

their attention on the wind generated-waves energy potential in the Southeast Asia region, showing that Vietnamese coasts exhibit a poor power output on average. The most important reference available on this energy source up-to-date is the KHCN-06-10 project [39], whose goal was to calculate the energy potential from sea wave in 83 sites along Vietnam's coastlines. The main outcome of the project was that Vietnamese coasts possess an abundant wave energy potential and that it directly depends on the regional monsoons, whereas a large wave momentum in Northeast, South, and Southwest directions is available in offshore areas [40].

This project classified Vietnamese coastal areas into 6 regions according to their wave energy potentials, showing that this RES promises good exploitation results, mainly in Zone 4 (South Central), Zone 2 (South of Gulf of Tonkin), and Zone 5 (Southern Delta), where the annual average wave energy flux reaches 30 kW/m, 25 kW/m and 18 kW/m, respectively. Furthermore, peaks up to 100 kW/m in selected regions in Zone 4 were recorded during December. If entrepreneurs took advantage of this source on a large scale, the coasts of Vietnam might provide several tens of GW from wave energy.

Case study for the onshore-nearshore location

Five promising installation points for each source were selected, as shown in Fig. 1(a) [33]. The pins for wind turbines (red pins) were selected investigating the local bathymetry [41] and limiting the investigation to the areas within 50 km from the coast and where depth is lower than 50 m, as per the current state-of-art technology [42]. Locations for wave converters (green pins) were not affected by depth since the converter is assumed to be installed on harbors. Furthermore, limiting the geographical areas to 50 km from the coasts should ensure that storms, which are a frequent issue along the East Sea between May and December [43], are less severe, preserving the integrity of the converters over their technical life. Electricity production in each location indicated in Fig. 1(a) was assessed using Eq. (1) and (2).

Case study for the offshore location

This case study involves the identification of the optimal renewable energy mix for a given region able to satisfy a given energy demand. The case study is focused on the province of *Ca Mau* (South Vietnam), whose coastline bathymetric map was investigated to find some promising installation points for RES technologies. As shown in Fig. 1(b), two locations were selected for wind farms (A and B), while a single location was identified (C) for the installation of the offshore prototype equipped with a PV module.

Results

Onshore-nearshore case study

The methodology described in Section "WEC concepts and techno-economic analysis" for the onshore-nearshore case study was utilized in the reference points illustrated in Fig. 1(a), considering the installation of a single WEC, and data on the average monthly energy resource were extrapolated from the maps in Figure 11 and Figure 12 [30]. The values of monthly average wave energy flux resulting from the simulations and the parameters shown in Table 6 in the Appendix C were used as input for Eq. (1), obtaining the results shown in Fig. 2(a). According to recent measurements [24], the efficiency of the onshore generator was set equal to 10% in Eq. (1).

Likewise, the annual electricity production of the wind turbines was calculated according to Eq. (2), using values of monthly average wind power density in the reference points illustrated in Fig. 1, the parameters shown in Table 6 (provided in Appendix C) and an average efficiency value of 26.6%, related to winds between 4 and 8 m/s distributed with a frequency well-fitted by the Rayleigh probability distribution function. The results of the simulations are reported in Fig. 2(b).

Using as a reference the available FIT for offshore wind farms in Vietnam, issued with Decision No. 21/QD-BCT [44] and equal to 1815.95 VND/kWh (corresponding to about 7.8 cUSD/kWh), the wave converter and the eight wind turbines do not result as profitable investments, although the FIT for offshore wind farms was the highest available for supporting RES in Vietnam. For this reason, the minimum attractive FIT was evaluated for each technology and for each installation point. The results are illustrated in Fig. 3, where the average values are shown using histograms, also showing the variability range in all reference points, including a sensitivity analysis assessed considering:

- for the wave energy converter, a variation of the investment equal to ±15% of the base value shown in Table 6 (in Appendix C);
- for wind turbines, the different models whose features are illustrated in Table 5 (in Appendix C).

The simulations show that the nearshore locations assessed in this study, although being among the most promising in the whole nation, would not be economically profitable for the installation of a wave converter or a wind farm with these economic conditions. In detail, the minimum attractive FIT ranges between 3 and 19 times the FIT

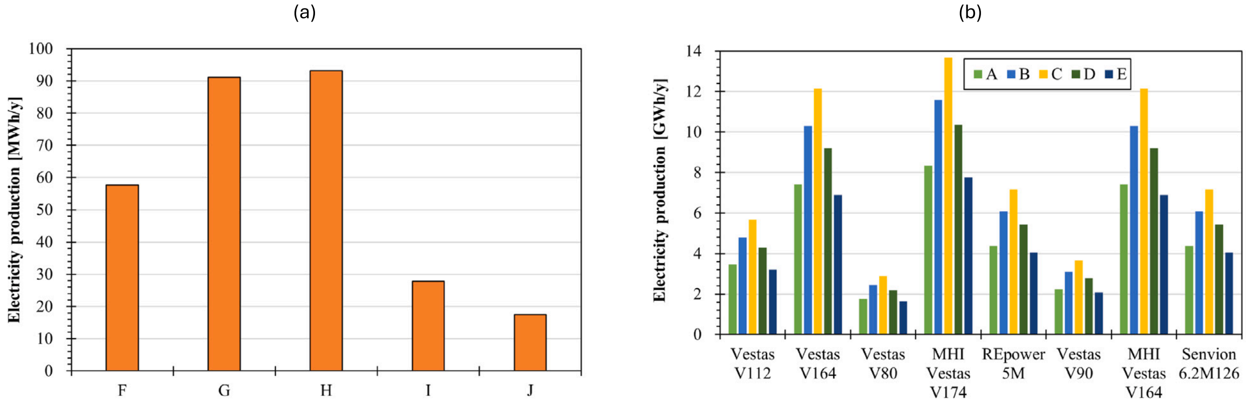
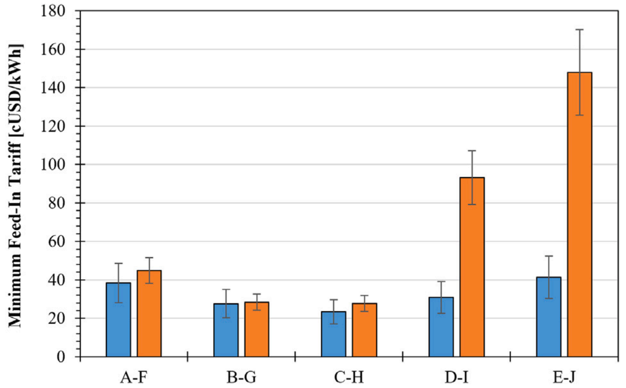


Fig. 2. Annual electricity production in the onshore-nearshore case study (a) from WEC and (b) from wind.



	A-F	B-G	C-H	D-I	E-J
🟦 wind	38.40	27.63	23.42	30.91	41.32
🟧 wave	44.89	28.40	27.78	93.11	147.94

Fig. 3. Minimum attractive FIT for wave and offshore wind energy in each reference point in the onshore-nearshore case study.

established for wind energy. Furthermore, for new projects, there is currently no regulation on FIT. Thus, since this simulation was performed on the most promising areas, we can state that, in order to support the introduction of wave energy in the Vietnamese context, a minimum FIT is required. Its value should be at least equal to those illustrated in Fig. 3, since other areas of the country have a lower energy density.

The adoption of these RES technologies in the national energy mix might help to decarbonize the current Vietnamese power system and help into reaching the net-zero emissions goal by 2050. A synthesis of the possible final energy and carbon reduction is illustrated in Table 1. For the latter quantity, the emission factor of the Vietnam current electricity generation mix, equal to 0.381 t CO_2/MWh, was gathered from [45]. This value was included as constant over the simulations, since the adoption of some renewable generators in a specific region of Vietnam cannot affect significantly the national carbon emission factor.

Offshore case study

The mathematical model for the offshore case study described in Section "WEC concepts and techno-economic analysis" for the offshore case study was implemented on a MS Excel spreadsheet and solved using the Solver function with the Evolutionary optimization algorithm.

Considering the climatic data from the literature for wave and wind energy [46,47] and using an online GIS tool for solar energy [48], the monthly production was evaluated for a single unit of each technology in the three selected points. These values are recapped in Table 2.

The algorithm described in Appendix D was applied to identify the optimal number of components for the three points adopting different desired RES share values. The output of the simulations is recapped in Fig. 4(a), while the corresponding annual operating costs, annualized investments, incomes, and profits are reported in Fig. 4(b). Both graphs show the results for different values of the fraction of the energy demand covered by the RES mix. The maximum share assessed in the present study is equal to 65% to limit grid issues related to uncertainties over intermittent renewable energy sources.

It is worth mentioning that the annual incomes and the annual profits were calculated considering that the electricity is remunerated with the FITs available until 2023 (0.078 USD/kWh for offshore wind and 0.065 USD/kWh for solar), using the value for offshore wind also for WEC technology. The detail of the LCOE, the total installed power, the actual shares of RES, the share of electricity production from sea wave and PV over the total RES production, the absolute energy production from RES and the avoided annual CO_2 emissions are provided in Table 3. For the latter quantity, as for the previous first case study, a constant emission factor was set [45].

With the FIT currently available in Vietnam for solar PV and offshore wind energy, equal to 6.5 cUSD/kWh and 7.8 cUSD/kWh, respectively, it is possible to perform a more detailed economic analysis with respect to the previous case study. In detail, the main economic parameters related to investment comparison were evaluated: Net Present Value (NPV), Return on Investment (ROI), Discounted Payback Period (DPB), and Internal Rate of Return (IRR) [31]. These additional outcomes are provided in Table 4. Analyzing these results, the first evidence is that the introduction of renewable energy systems in the *Ca Mau* Province would be always economically profitable, apart from the case with 65% share, as well as causing huge environmental benefits in terms of avoided CO_2 emissions.

Further investigating Table 4 we can state that the highest is the investment, the highest is the resulting NPV, with the most convenient being the case with 60% RES share, as can also be seen in the blue trend in Fig. 4(b) with reference to the annual profit.

The remaining three economic indicators would suggest preferring a 5% or 10% share, although the values for 65% share are quite similar. Last, with respect to the RES electricity and avoided emissions shown in Table 3, these trends linearly increase with the RES share.

Conclusions

In this paper, two energy generator concepts exploiting wave energy were proposed, one for onshore and one for offshore application. After describing the main features of each device, the possible integration of these systems in the context of the Vietnamese energy system was investigated with two case studies. Furthermore, a literature review on the wave energy potential was provided with specific reference

Table 1
Annual RES electricity production and avoided emissions per each generator model in the onshore-nearshore case study.

Generator	RES electricity production [MWh/year]	Avoided carbon emissions [tCO_2/year]
Wave converter prototype	26–140	10–53
MHI Vestas V164-10.0MW	6,900–12,193	2,629–4,645
MHI Vestas V174-9.5	7,767–13,725	2,959–5,229
Vestas V164	6,900–12,193	2,629–4,645
Senvion 6.2M126	4,073–7,197	1,552–2,742
REpower 5M	4,073–7,197	1,552–2,742
Vestas V90	2,078–3,672	792–1,399
Vestas V112	3,218–5,687	1,226–2,167
Vestas V80	1,642–2,902	626–1,106

Table 2
Unit production from RES in the selected points for the offshore case study.

Rated power [kW]	Wind turbine		Sea wave converter	PV module
Ref. points	4200 A	4200 B	80 C	10.82
	Unit production [MWh/month]			
January	1551.4	2861.0	24.25	1.17
February	965.5	2426.1	23.65	1.32
March	1135.9	2308.4	20.68	1.56
April	847.2	1365.6	10.08	1.46
May	1621.8	1135.9	5.21	1.28
June	1907.6	1365.6	13.68	1.08
July	2308.4	1762.3	18.15	1.08
August	3129.4	2686.0	11.16	1.20
September	2540.8	2105.4	8.21	1.05
October	1621.8	1621.8	4.91	1.14
November	2297.1	2599.4	8.21	1.05
December	2373.7	3275.6	29.16	1.07

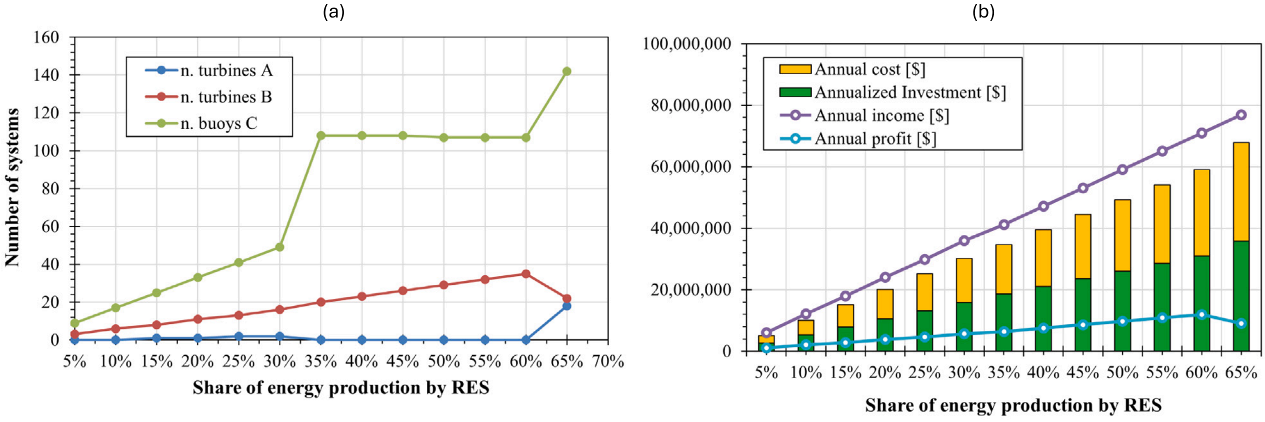


Fig. 4. Results in the offshore case according to the share of RES production. (a) number of devices required to achieve a fixed RES share and (b) overview of annual O&M costs, investment costs, incomes, and profits.

to the Vietnamese context. The utilization of this energy source to produce electricity may help this country in the current phase of economic growth that forced energy development and decarbonization, with the further advantages of avoiding the exploitation of lands and reducing the distances between power plants and loads and reducing the electricity transport losses.

The outcomes of the case study in the onshore-nearshore scenario suggest the adoption by the government of a minimum FIT equal to 23.42 cUSD/kWh and 28.40 cUSD/kWh for wave and wind technologies, respectively, with reference to the best cases, namely reference point H for sea wave and point C for wind. This means that the current FIT for offshore wind technology (9.80 cUSD/kWh) should be almost triplicated. On this aspect, the authors further investigated the economic feasibility of the currently existing offshore wind farms in Vietnam in Appendix E. Furthermore, notwithstanding offshore wind turbines are in a more advanced development status than the WEC systems, the tariff for the latter technology would be lower than the value related to offshore wind technology.

It should be highlighted that the value adopted for the unit investment cost for offshore wind turbines, being an average literature value in the ASEAN region, seems to be somehow overestimated since it is known that the unit investment was equal to 2209 USD/kW for an existing farm in Vietnam [49]. Nevertheless, the investment in wind farms would not be profitable as well if this latter value and the current FIT were adopted in the five points selected in this study.

The results of the second case study prove that a massive introduction of offshore RES in Vietnam is economically feasible. The selecting algorithm was applicable up to a share equal to 65% since a higher share would violate the third condition in Eqn. 15 in the Appendix D. This aspect can be seen in Fig. 4(a), where, with reference to the case with a RES share equal to 65%, the solver increases the number of wind turbines installed on the B point rather than on the A site for the best

Table 3
Main features of the suggested energy mixes in the offshore case study.

Share [%]	LCOE [cUSD / kWh]	Installed Power [kW]	Actual RES Share [%]	WEC + PV share [%]	RES ele. prod. [MWh / year]	Avoided emissions [kt CO_2 / year]
5%	6.46	15,817	5.12	2.21	78,266	29.8
10%	6.45	31,544	10.22	2.09	156,339	59.6
15%	6.54	47,270	15.11	2.07	231,201	88.1
20%	6.52	62,997	20.21	2.05	309,275	117.8
25%	6.56	78,723	25.11	2.05	384,136	146.4
30%	6.54	94,450	30.21	2.03	462,210	176.1
35%	6.54	109,808	34.71	3.90	530,978	202.3
40%	6.52	124,808	39.71	3.41	607,517	231.5
45%	6.50	139,808	44.71	3.03	684,057	260.6
50%	6.48	154,717	49.70	2.70	760,404	289.7
55%	6.47	169,717	54.70	2.45	836,943	318.9
60%	6.46	184,717	59.71	2.25	913,483	348.0
65%	6.86	212,896	64.70	2.75	989,938	377.2

Table 4
Economic analysis for the offshore case study.

Share [%]	Investment [kUSD]	O&M [kUSD/y]	Income [kUSD/y]	NPV [kUSD]	ROI [%]	DPB [years]	IRR [%]
5%	45,653	2,397	6,084	4,461	9.8%	17.4	5.1%
10%	91,017	4,791	12,155	9,080	10.0%	17.4	5.1%
15%	136,381	7,185	17,976	10,294	7.5%	18.0	4.8%
20%	181,745	9,579	24,047	14,913	8.2%	17.8	4.9%
25%	227,109	11,973	29,868	16,126	7.1%	18.1	4.8%
30%	272,473	14,367	35,939	20,745	7.6%	17.9	4.8%
35%	318,239	16,123	41,167	22,160	7.0%	18.1	4.8%
40%	361,289	18,493	47,137	28,042	7.8%	17.9	4.9%
45%	404,339	20,863	53,107	33,925	8.4%	17.8	4.9%
50%	447,100	23,230	59,065	39,966	8.9%	17.6	5.0%
55%	490,150	25,600	65,035	45,848	9.4%	17.5	5.0%
60%	533,200	27,970	71,005	51,731	9.7%	17.4	5.1%
65%	615,074	32,025	76,888	−5,297	−0.9%	20.3	3.9%

solution, where the annual production is lower and with a different profile during the year. This is the reason behind the non-linearity of the trends for wind turbines in Fig. 4(a) and for annual profit in Fig. 4(b).

Regarding the economic and environmental aspects, the simulations reveal that high economic revenues are achievable in this sector since the LCOE values obtained in the case study is lower than the FIT proposed by the current regulation and that huge emissions savings may be attained since the energy mix is still massively made up of fossil fuels-fired power plants.

The present study was intended as a starting point to investigate the economic and technical potential for the installation of RES in Vietnam, with a special focus on the WEC technologies described in Section "WEC concepts and techno-economic analysis". Future works might couple the RES installation to the significant power grid issues, assessing the local congestions and the possible installation of storage systems to allow a better exploitation of the renewable sources available in this country.

Abbreviations

The following abbreviations are used in this manuscript:

DPB	Discounted PayBack Period
FIT	Feed-In Tariff
IRR	Internal Rate of Return
LCOE	Levelized Cost Of Energy
NPV	Net Present Value
O&M	Operations & Maintenance
PV	PhotoVoltaic
RES	Renewable Energy Sources
ROI	Return On Investment
UCRF	Uniform Capital Recovery Factor
WEC	Wave Energy Converter

CRediT authorship contribution statement

Domenico Curto: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Doan Van Binh:** Writing – review & editing, Conceptualization. **Luong Ngoc Giap:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Le Thi Thuy Hang:** Writing – original draft, Formal analysis, Data curation. **Francesco Montana:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nguyễn Quang Ninh:** Writing – review & editing, Formal analysis, Data curation. **Eleonora Riva Sanseverino:** Writing – review & editing, Formal analysis, Conceptualization. **Giuseppe Sciume':** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.seta.2025.104268.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

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