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Economic Analysis of Floating Photovoltaic Plants in Black Sea

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ABSTRACT

Purpose:
The main aim of the study was to estimate the levelized cost of electricity (LCOE) for a photovoltaic island project in the offshore area of Romania and the most effective possibilities to increase its profitability by reducing this indicator.

Design/methodology/approach:
The present study involves the analysis of the profitability of such an investment in the offshore area of Romania (considering CAPEX, OPEX, annual productivity and the levelized cost of energy), as well as the benefits it brings for the national energy system in periods of high deficit, such as those of drought or with low wind, and for the balancing activity in periods of instability.

Findings:
The LCOE for a floating photovoltaic park in the Romanian offshore area of the Black Sea can reach 211,303 euros/MWh, but this can be considerably reduced by increasing the installed capacity. This is due to the high costs of connecting to the terrestrial network. Also, costs can be reduced by combining the installed capacities of photovoltaic and wind energy production.

Research limitations/implications:
The main limitation of the research is that the possible discounts that can be obtained by an investor for the purchase of materials and their installation were not taken into account. Also, their prices can fluctuate considerably depending on the current realities of the international market.

Originality/value:
Photovoltaic plants are already one of the main renewable energy sources that Europeans rely on in the race to achieve the climate neutrality. In addition, in contrast to the wind farms, they are easier to manage and can even support the balancing of national energy systems, their production capacity being forecasted more easily. Since the main shortcoming of this source is the vast territory occupied by the installed panels, a solution already adopted worldwide is to install them on the surface of the inland waters or in offshore areas. Even if in these cases the installation and maintenance is more expensive, the land acquisition costs are lower or non-existent and the benefits for the environment are much more significant.

Keywords:
Renewable energy, photovoltaic, offshore, Black Sea

1. Introduction

The energy produced by photovoltaic parks is one of the most widespread types of renewable energy worldwide, along with that produced by wind turbines. The possibility of predicting its volatility with high precision is one of its main advantages, being possible to use it to balance the transmission system. The same cannot be said for wind farms, whose volatility is greater so the possibility to predict their production is less.

However, the positions are reversed when it comes to the space occupied by the installations used, since wind turbines can have installed powers of 0.5 and 1.5 MW per module for propellers with diameters of up to 100m, while photovoltaic parks occupy between 1 and 1.6 ha of land for an installed power of 1 MW (Wirth, 2023). Thus, for the installation of these production capacities, it is necessary to identify areas whose use for other economic activities, such as agriculture, is not more profitable than the production of electricity.

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Over time, there have been identified methods by which the space occupied by photovoltaic panels would not be unavailable, thus, they are installed on buildings or above irrigation canals to reduce water evaporation, but these spaces are not large enough to ensure some large productions. Thus, for onshore parks, as a rule, investors chose outside the built-up area lands which are removed from the agricultural circuit or not used by the owners.

The objective of the present study is to analyse the profitability of installing these production capacities in the offshore area, where the impact on the environment is almost non-existent and the occupied area is not limited by the costs of land acquisition or relief. Also, the research proposes the identification of some methods of reducing its investment costs and maximizing its profitability. This will be achieved by estimating the levelized cost of electricity (LCOE). Subsequent, the identification and testing of some methods to reduce this indicator will show what is the minimum cost of the investment that can guarantee or maximize its profitability.

The analysis intends to contribute to identifying viable solutions for increasing renewable energy production capacities in profitable conditions, especially in areas where the unavailability of agricultural land cannot be a solution. For this reason, the study is objective and aims to model as accurately as possible the real costs and profitability for such an investment.

Also, with the exhaustion of the land necessary for the installation of photovoltaic parks in the European Union, investors will have to turn to other solutions. A possibility to continue the expansion of renewable energy is the use of the offshore area, where a combination between wind turbines and photovoltaic panels could assure a constant energy production. There are also situations where the offshore area is already seen as a solution for the installation of wind farms and photovoltaic panels, such as those in island areas where there is not enough land available.

2. Review of Literature

Although investments in renewable energy register the highest values in history, the worldwide growth rate of electricity consumption is still higher than that of the increase in production capacity from renewable sources (Elomari et al., 2022). However, the technologies in the field are evolving rapidly, and the increase in their efficiency, the lifetime of the equipment and the reduction of material costs will make renewable energy more and more attractive and profitable (Obeidat, 2018).

Until now, most wind and photovoltaic farms have been installed on land, where investment is cheaper and easier to achieve. However, both technologies can be adapted to be installed in offshore areas, where renewable energy farms can be spread over much larger areas and power density is higher and more stable (Costoya et al., 2022). In addition, the installation of floating wind energy farms reduces the competition for the free land and offers the possibility of using it for other economic activities, such as agricultural or industrial ones (Lee et al., 2014; Ramasamy and Margolis, 2021).

Analyzing worldwide historical data from the last 40 years, Silalahi and Blakers (2023) consider that water surfaces around sea coasts where waves higher than 4 meters and winds with speeds higher than 15 m/s are not encountered can support the production of 220 thousand TWh from photovoltaic panels, which would provide power consumption for 11 billion people. Wang and Lund (2022) already consider floating PV platforms to be a relatively mature renewable energy production option, with many companies already providing a variety of technical solutions.

Installing photovoltaic panels on water implies other benefits, both for the environment, such as reducing the evaporation process when they are placed on lakes (Ferrer-Gisbert et al., 2013), and for the investor itself, because the water temperature is lower and more constant compared to that on land so the energy generation efficiency could increase (Young-Geun et al., 2014). Studies carried out so far have shown that photovoltaic farms installed on water can produce up to 10% more energy than those on land, due to the higher energy conversion efficiency caused by the lower temperatures of the water surface (Skoplaki and Palyvos, 2009; Kamuyu et al., 2018). These benefits were also highlighted by Tina et al. (2021), who experimentally showed that the collected energy increases considerably due to the cooling of the photovoltaic panels.

In addition to the advantage of cooling the panels, their location on the water also offers the possibility of orienting them according to the azimuth angle without considerable costs. Bozikova et al. (2021) showed that tilt angle and azimuth angle are some of the most important influencing factors for the energy production efficiency of photovoltaic panels.

The installation of offshore photovoltaic islands also involves challenges, such as identifying the most suitable floating and anchoring systems for the entire site or estimating the height of the waves. Claus and Lopez (2022) exemplified 4 categories for mooring layouts (catenary, taut mooring, compliant mooring and rigid mooring) and 4 for anchoring systems (dead weight, suction foundation, drag anchor and embedded anchor). Also, they classify the pontoon type in 3 classes. The first provides rafts made of HDPE (high-density polyethene) pipes connected with steel or aluminum. The second class, designed for freshwater applications, is a single float system made of HDPE with built-in rails which hold the photovoltaic panels. In the third class, the floats are assembled in a large floating platform which is connected to a stainless-steel structure.

Muaddi and Jamal (1992) showed that covering the panels with a thin layer of water can increase their efficiency and lifetime, not decrease it, due to its cooling effect. On the other hand, the existence of waves increases the exposure of the structure to saltwater, which is corrosive, thus requiring the use of more resistant and more expensive, materials (Ghigo et al., 2022). Wei et al. (2023) proposed the installation of breakwaters around the photovoltaic islands to avoid the impact of waves on the platforms by reducing their heights with 40%. In the area of the Romanian coast, the average wave height is 0.95 meters - only 1% of them exceed 3.7 meters - with a slope between 0.02 and 0.04 and an average period of 5.1 seconds (Omer et al., 2020). Also, the highest waves occur between December and January, and the lowest in June and July opposite to the period of maximum and minimum photovoltaic power output (Figure 5).

However, in practice it has been shown that waves are not necessarily the biggest threat to a photovoltaic island. The Oceans of Energy project, installed in the North Sea, withstood storms in 2020 that produced waves with heights of 9-10 meters, although its structure does not provide protection mechanisms against them (Oceans of Energy, 2021). The installation of islands of photovoltaic panels in the offshore area is being tested worldwide. For example, Vlaswinkel et al. (2023) believe that future projects in the offshore area of the Netherlands that will follow the Oceans of Energy model will be located on areas of more than 10,000 m2 and will be installed in areas with depths of 20-30 meters, in the approach of wind farms (Oceans of Energy, 2021).

Regarding the profitability of investments in floating photovoltaic panels, the analysis carried out by Micheli and Talavera (2023) showed that for the projects installed on continental waters the net present value is considerable positive in Turkey, Romania, Italy, Spain, Bulgaria and Greece. Also, the solution of placing photovoltaic panels on water can be adopted especially in the case of islands, where the land surface is small and, often, conventional and polluting production capacities are used because of the lack of alternatives (Vo et al., 2021).

The future of floating photovoltaic farms depends on how and at what pace the technology used and its costs are going to evolve, as well as its ability to create a synergy between it and other types of renewable energy, like wind turbines (Oliveira-Pinto and Stokkermans, 2020). If in the case of freshwater, they must work in addition to hydropower plants, in the case of marine environment it may be necessary to combine them with wind energy to optimize investment costs.

Pascasio et al. (2021) and Ghigo et al. (2020) consider that the production of renewable energy by combining wind and photovoltaic farms is the best option, especially in the case of off-grid islands that usually use energy produced by diesel generators. Until 2050, European states have assumed to install 300 GW of offshore wind farms in all sea basins to which the European Union has access (European Commission, 2021). These capacities can be combined with floating photovoltaic farms and will contribute decisively to achieving the climate neutrality.

3. Methodology

In order to identify the time horizon in which the project could be carried out, the Romanian transmission operator's projection for the development process of the national electricity system was also consulted, so as to identify the year in which production could be started.

Subsequently, it was necessary to identify the location where the island would be located on the surface of the sea and near the coast, because large parts of this offshore area are registered as Natura 2000 sites, and the project could affect the biodiversity of these protected areas. In this case the authorization necessary for environmental protection would be almost impossible to be obtained.

The calculation of LCOE for renewable energy production is essential to be carried out specifically for a certain point on the map to ensure the viability and correctness of the results. In the case of renewable energy, it is very important that the LCOE analysis must take into account the geographical and climatic specificities of the area, as well as the capacity of the electricity transmission system to integrate new production capacities with large power variations (more difficult to balance).

After identifying the location where the island of photovoltaic panels could be located, its characteristics considered relevant for identifying the production capacity were calculated - direct normal irradiation (DNI), global horizontal irradiation (GHI), diffuse horizontal irradiation (DIF), global tilted irradiation at optimum angle (GTIopta), optimum tilt of PV modules (OPTA), air temperature (TEMP), terrain elevation (ELE), total photovoltaic power output and global tilted irradiation.

Subsequently, costs were calculated for the components of the islands: the metal structure, the floating system, the anchoring system, the interconnection with the shore and the panels used. AISI 205 stainless steel and 5005 aluminum were considered for the structure due to its good corrosion resistance in the marine environment. For the floating system, Floating HDPE modules were chosen, each piece having the capacity to support floating for 1200 kg and dimensions of 1400x850x550 mm. Regarding the panels, the Monocrystalline Jinko Tiger Neo TOPCon N-Type 54 Rectangular cell model was chosen, with 435Wp per panel, which offers a good quality-price ratio and one of the best efficiencies on the market.

The structure of the pontoons can be classified in class 3, according to the classification proposed by Claus and Lopez (2022). HDPE floating pontoons are attached to stainless steel 205 bars, and the panel fastening system is made of aluminum 5005. This type of structure is suitable for the marine environment, having the ability to withstand large waves, although on the Black Sea coast considerable waves were recorded only in extreme situations.

Finally, the total energy produced by the photovoltaic island was calculated, according to the formula:

$$E = A \times f \times H \times Pr \quad (1)$$

Where E is the energy yield (kWh), A is the panel area (m^2), f is the efficiency or solar panel yield (%), H is the global tilted irradiation (kWh/m2) and Pr means the performance ratio, indicating the losses overall effect on the

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photovoltaic system output due to temperature, system inefficiencies or failure. According to Markos and Sentian (2016), Pr was estimated at 75%, its default value.

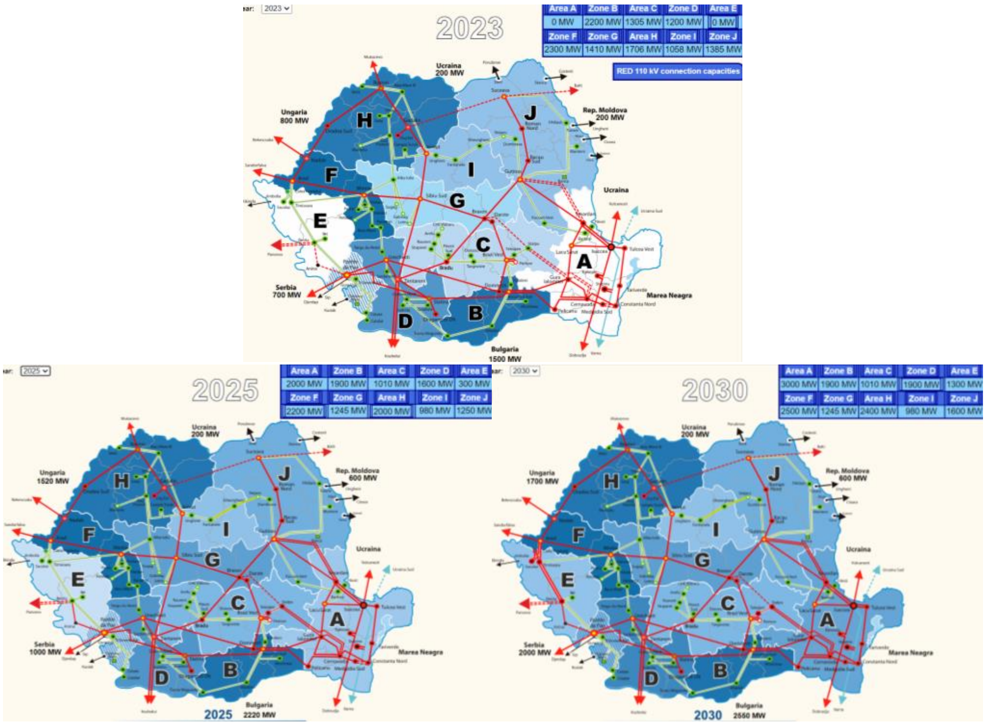
After calculating CAPEX, OPEX, and of the total energy production in a year, LCOE was calculated. This indicator is a measure of the average net present cost of electricity generation for a production capacity over its lifetime.

The LCOE calculation formula used to estimate it in the study is:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{P_{el}}{(1+r)^t}} \quad (2)$$

Where n is the total years of operation, $OPEX_t$ is the value of the OPEX for the year t, P_{el} is the electricity produced in one year, r is the discount rate.

4. Results



Area A	Zone B	Area C	Zone D	Area E
0 MW	2200 MW	1305 MW	1200 MW	0 MW
Zone F	**Zone G**	**Area H**	**Zone I**	**Zone J**
2300 MW	1410 MW	1706 MW	1058 MW	1385 MW

Area A	Zone B	Area C	Zone D	Area E
2000 MW	1900 MW	1010 MW	1600 MW	300 MW
Zone F	**Zone G**	**Area H**	**Zone I**	**Zone J**
2200 MW	1245 MW	2000 MW	980 MW	1250 MW

Area A	Zone B	Area C	Zone D	Area E
3000 MW	1900 MW	1010 MW	1900 MW	1300 MW
Zone F	**Zone G**	**Area H**	**Zone I**	**Zone J**
2500 MW	1245 MW	2400 MW	980 MW	1600 MW

Figure 1. Available capacity to take over electricity production in the national grid

Source: www.transelectrica.ro

Although for area A, where the energy produced by the photovoltaic system will be introduced, the transport infrastructure is already undersized, the investment plan of the transport operator provides for the development of an additional capacity of 2000 MW by 2025 and 3000 MW by 2030 (Figure 1).

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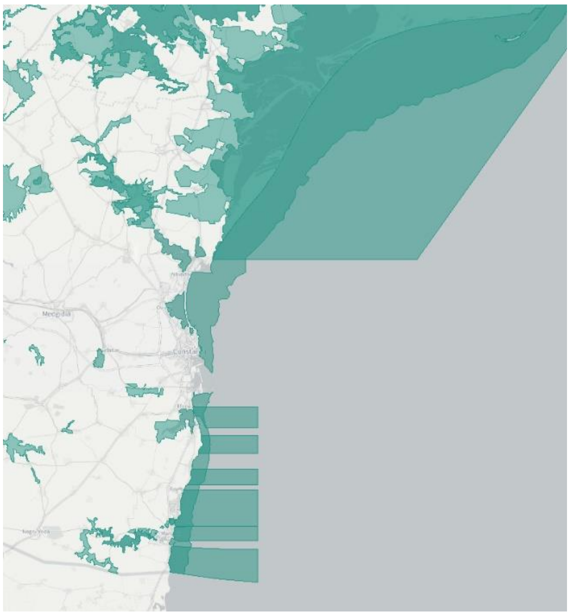

Figure 2. Romanian Natura 2000 sites in 2023

Source: www.utility.arcgisonline.com

The coordinates of the land identified as the most suitable for the floating photovoltaic plant are 44°03'51", 028°41'10", located off the town of Eforie Nord, according to Figure 3.

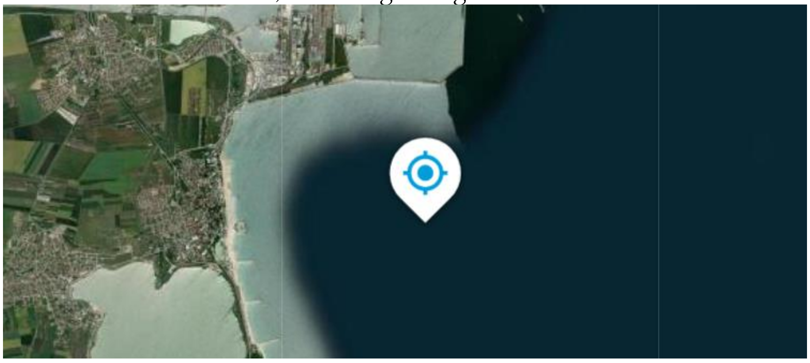

Figure 3. The location for 44°03'51", 028°41'10"

Source: www.globalsolaratlas.info

The distance from the coast is high enough so that the location does not interfere with protected areas and does not affect marine flora and fauna. Also, the depth of 21 meters is shallow enough that the mooring system is not too expensive, but it also involves considerable costs for the installation of marine cables.

This section presents the empirical findings and interpretations of the research.

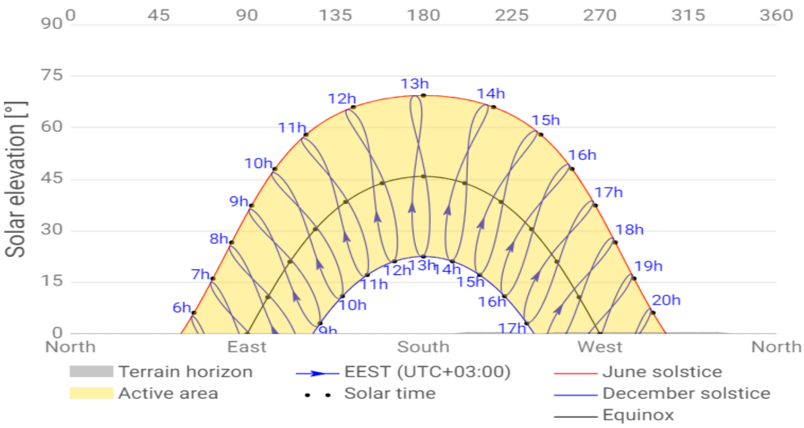

Figure 4. Solar azimuth and solar elevation

Source: www.globalsolaratlas.info

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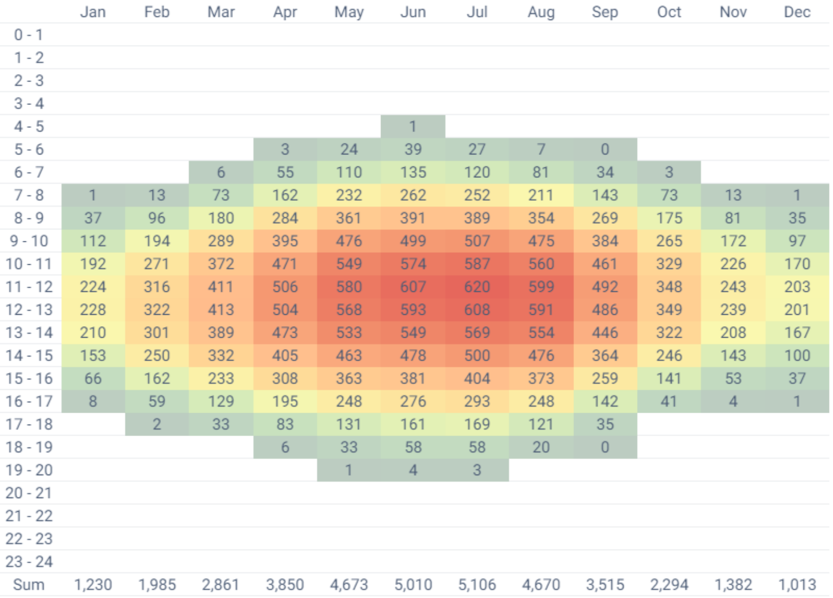
Furthermore, Figure 4 shows the solar azimuth and the solar elevator, calculated using the Global Solar Atlas software for the selected coordinates. Its impact on the production of photovoltaic panels has already been shown in many of the previous studies on this topic (Tang et al, 2012; Stanciu et al, 2016; Hafez et al, 2017). Also, in Table 1 it can be observed the characteristics of electricity production in this area, estimated with Global Solar Atlas.

Table 1. Characteristics of electricity production in the selected area

Site analysis indices	Value
DNI	1350.7 kWh/m2
GHI	1415.1 kWh/m2
DIF	613.4 kWh/m2
GTIopta	1623.1 kWh/m2
OPTA	32/180°
TEMP	13.1 °C
ELE	-21 m
Total photovoltaic power output for 1000 kWp	1.146 GWh/year
Global tilted irradiation	1523.6 kWh/m2 per year
Panel's tilt	10°
Panel's azimuth	180°
Distance from shore	3500 m

Source: Authors' results, based on data from www.globalsolaratlas.info

In Figure 5 and 6 the total photovoltaic power output for 1 MWp capacity is illustrated. Depending on this, it can be seen the period of the year and of the day when the production will register the highest values.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5						1						
5 - 6				3	24	39	27	7	0			
6 - 7			6	55	110	135	120	81	34	3		
7 - 8	1	13	73	162	232	262	252	211	143	73	13	1
8 - 9	37	96	180	284	361	391	389	354	269	175	81	35
9 - 10	112	194	289	395	476	499	507	475	384	265	172	97
10 - 11	192	271	372	471	549	574	587	560	461	329	226	170
11 - 12	224	316	411	506	580	607	620	599	492	348	243	203
12 - 13	228	322	413	504	568	593	608	591	486	349	239	201
13 - 14	210	301	389	473	533	549	569	554	446	322	208	167
14 - 15	153	250	332	405	463	478	500	476	364	246	143	100
15 - 16	66	162	233	308	363	381	404	373	259	141	53	37
16 - 17	8	59	129	195	248	276	293	248	142	41	4	1
17 - 18		2	33	83	131	161	169	121	35			
18 - 19				6	33	58	58	20	0			
19 - 20					1	4	3					
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	1,230	1,985	2,861	3,850	4,673	5,010	5,106	4,670	3,515	2,294	1,382	1,013

Figure 5. Average hourly photovoltaic power output
Source: www.globalsolaratlas.info

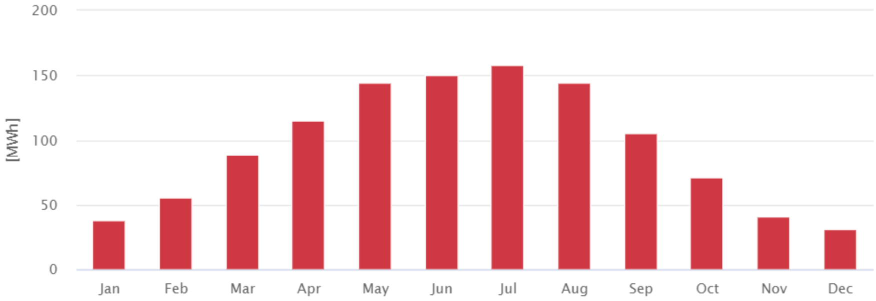


Figure 6. Total photovoltaic power output per mounth
Source: www.globalsolaratlas.info

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For the investment calculation Monocrystalline Jinko Tiger Neo TOPCon N-Type 54 Rectangular cell Black Frame Solar Panel, cu 435Wp was chosen. The mentioned panels offer good resistance to salinity and fog and the average price on the market is 157 euros per piece.

Table 2. Panel characteristics

Jinko Tiger Neo TOPCon N-Type 54 Rectangular cell solar panel	Value
Rated power	435 W
Efficiency	21.6%
Width	1,134 mm
Height	1,722 mm
Occupied area	1.952748 m2
Mass	22kg
TEMP coefficient	-0.04%
Minimum product warranty	15 years

In the present paper, estimated energy produced was 481.9835 kWh per year for one photovoltaic panel.

To install a power of 1,044 MW, 2400 panels with an installed power of 435 W are needed. In the context in which a panel introduces annually 481.9835 kWh into the network in the present situation (according to the specificity of the area) the photovoltaic island could introduce into the system a total of 1.15676 GWh per year.

Without considering the distances required to be left between the panels to carry out maintenance activities and to ensure the flexibility of the platform, they would occupy an area of 4686.5952 m2. In order to ensure the functionality of the project (maintenance activities), it is considered necessary to create a passageway around each platform with a width of 0.5 meters. Thus, the total of 200 platforms, connected by hinge systems that will ensure their mobility during periods of high waves, would occupy 6760 m2. The total mass of this site was estimated at approximately 265 tons.

The materials considered for the construction of the platform are stainless steel AISI 205 (4.2 euros per kg), aluminum 5005 (2.2 euros/kg) and HDPE (1.4 euros/kg), the prices for these being the international averages in the last month of the period carrying out the study. For each platform with 12 panels, 4 HDPE floats were considered with a value of 220 euros per piece, resulting in a total cost of 176 thousand euros for the floating system.

For fixing the pontoons on each side, steel bars were chosen (4 rows each, to which 2 more are added in the middle to ensure the strength of the platform). On the side, to ensure the access, but not to make the platform unnecessarily heavier, an aluminum strip with a width of 0.5 m was considered to be installed. As a support for the installation of the panels, 4 rows of aluminum bars should be installed above the structure.

For each platform, 2 interconnections with the neighboring platform were considered. They are made through steel bars (1 m long, 10 cm wide and 2 cm thick) hinged to ensure the mobility, but to prevent the collision between the platforms.

The calculation of the cost for anchoring the platform was made according to the model used for wind turbines, proposed by Alberto et. Al (2022). For the depth of 21 m, as is the case of the realized location, the anchoring of the platform with a steel cable with a diameter of 8 cm and a length of 30 m was chosen for a semi-extended anchorage (semi-taut layout), which would allow the flexibility of the platform in periods with waves. The calculated weight of each steel cable is 117,636 kg, and 20 anchors would be used for the entire platform, so that one cable is provided for every 10 platforms.

According to the estimates made by Ghigo et al. (2022) for floating offshore wind platforms, the marine cables which connect the platforms to the shore were estimated at 600 euros per meter (amount that also includes the installation), and the cement required for the anchoring system at 600 euros per ton. Also, the costs of cabling and connection to the power grid, the security system and the monitoring software were estimated at 500 euro/kW and the manufacturing and assembly work was considered 20%.

Table 3. CAPEX

	Costs per platform (euro)	**Total costs (euro)**
Materials used for the structure of the island		
Aluminium structure	284.1	56,820
Aluminium platform	157.9	31,580
Stainless steel AISI 205 structure	3,567.48	713,496
HDPE+Aluminium+WPC floating docks	880	176,000
Total		977,896
Photovoltaic panels		
Monocrystalline Jinko Tiger Neo TOPCon N-Type 54	1884	376,800
Clamping screws	48	9600
Invertor	-	30,000
Cabling, connection to the power grid, the security system and the monitoring software	468.58	468,198
Total		884,598
Connection and anchoring system		
Marine export cables	600 euro/m	2,100,000
Anchor system (stainless steel cables and concrete)	-	23,900
Connection between platforms system	-	39,312
Total		2,163,212
Assembly and material transport estimation (20%)		20%
Total		4,830,847

OPEX includes maintenance costs, facility inspection and transport charges paid to the national system operator. It was estimated at 15 euros/kW per year (totaling, in the first, 15,660 euros), with an annual increase of 0.2%. The lifetime of the panels was estimated at 20 years, and the production reduction was considered to be 0.4% per year, according to the manufacturer's specifications.

The state aid offered in Romania is 425,000 Euro/MW, so for the analyzed project it is 425,425 euro for solar energy state aid, and the conditions that must be respected by the project are: efficiency of monocrystalline panels over 19%, solar radiation over 1000W/m2, the air mass of 1.5 AM, and the cell temperature of 25°C (all of them being respected).

Table 4. Estimated costs, production and LCOE for multiplied platform

Number of platforms	CAPEX (euro)	OPEX (euro)	Total lifetime costs (euro)	Production during lifetime (MWh)	LCOE (euro/MWh)
1	4387933	319222.8	4707155.8	22276.81	211.303
2	6582654	638445.6	7221099.6	44553.62	162.0766
4	10972096	1276891	12248987	89107.24	137.4634
8	19750980	2553783	22304763	178214.5	125.1568
16	37308748	5107565	42416313	356429	119.0036

5. Discussion

Although LCOE registers a high value compared to other countries, such as Italy, where similar sites have registered LCOE of 150 euro/MWh (Lopez et al, 2022), but it can be observed that a large part of the CAPEX is represented by the connection of the platforms to the shore, so the multiplication of interconnected platforms would generate considerable economies of scale. Thus, for 2 islands located at the same coordinates, the LCOE would register 162.07 euros/MWh, for 4 locations it would decrease to 137.46 euros/MWh, and for 8 islands to 125.16 euros/MWh. In this context, for the panel island to be truly competitive, it would be necessary to install approximately 4,176 MW, which would involve the use of 9,600 panels and would occupy 27,040 m^2. The more times the project is multiplied, the lower the LCOE, but the larger the occupied area.

In addition, there is the possibility of obtaining additional funds through European grant programs, which could considerably reduce the investor's contribution to the CAPEX payment. Also, at the moment, for photovoltaic parks with an installed power of over 500 kW, in Romania, for every 1 MWh introduced into the system by the photovoltaic park, the operator receives a green certificate worth at least 29 euros. In the study, these certificates were not considered for the LCOE calculation. Also, in the case of contracting additional funds from European sources or from the state budget, CAPEX could decrease considerably, thus making it possible to increase the profitability of the installation.

Therefore, the most interested in such solutions could be communities on small islands, where the land available for installing panels is limited and expensive, and their coverage would affect local agricultural activities. In the offshore area, increasing the surface area occupied by photovoltaic panel islands is not a problem, since the marine environment is not affected, and the available space is very large. It is only necessary to avoid maritime transport routes, tourist areas and those where there is a risk of producing waves higher than the structure could withstand.

The present study analyzes the installation of floating islands in an open maritime area, the resulting LCOE being quite high, but it can also be reduced by identifying more favorable areas. For example, gulf areas and those which are protected by artificial dikes can be used more easily for the installation of floating panels due to the reduced risk of strong waves. This option can even lead to a reduction in investment costs, if installation on a lower or weaker structure is possible.

The main limitation of the present research is that it did not consider the possible discounts that could be made by the manufacturers of equipment and raw materials for the purchase of large quantities, which could reach, in some cases, up to 20%. In addition, costs for maintenance would also be able to decrease with the expansion of the platforms, similar to economies of scale. In addition, the 20 years lifetime considered for panels could be increased due to lower water temperatures.

Another limitation of the study is the fluctuation of prices on the international market for the equipment considered and for the materials used in the construction of the island structure. The instability of prices charged by manufacturers, the current risk of changes in the tariff policies as well as inflation may cause changes in CAPEX and OPEX.

5. Conclusion and Recommendations

The main purpose of this study is to objectively analyse the opportunity of installing photovoltaic islands in offshore areas from an economic point of view, but also to offer some solutions to increase the profitability of these investments. In the context of the energy transition, it is important that these technologies can become a viable solution for areas that experience difficulties in identifying large areas of land suitable for the installation of photovoltaic plants, such as islands.

Also, a solution for islands or other isolated areas, which could be united in energy communities, is to combine investments in photovoltaic energy production with those in wind energy (where the speed and constancy of the wind allows) or with storage capacities that can ensure consumption during the night. It should be noted, however, that the installation of batteries involves considerable additional costs.

LCOE decreases as the surface area of photovoltaic panels increases, but this decrease slows down, as it is mainly generated by the reduction of the costs of connection to the shore (submarine cables). According to the analysis, the costs can reach the profitability zone, but it is necessary to significantly increase the initial investment and have sufficient capacity of the transmission network to integrate the new production into the system.

A good method of making an offshore photovoltaic park profitable is to combine it with offshore wind farms, whose production capacity, although more volatile, is much higher than that of photovoltaic panels. Thus, the creation of wind and photovoltaic parks at sea can ensure the functionality of the two renewable resources without costs for the purchase or rental of onshore lands and with a considerably reduced CAPEX thanks to the savings made on the purchase of marine cables.

Also, the study showed that a small photovoltaic platform of only 1 MWh would not be profitable and a solution that would work for the investment is to multiply it in order to reduce the grid connection costs. The higher the production capacity, the lower the LCOE. Thus, similar to the assessment of Wang and Lund (2022), the technology is mature and can be a solution for increasing the renewable energy production.

Such investments are necessary to achieve the objectives stipulated in the Green Deal and indispensable for achieving climate neutrality. This is the reason why they could become more and more profitable with the passage of time and their technical optimization.

Continuing EU funding measures to finance investments in renewable energy production is still essential to ensure its profitability. In addition, with the increasing share of these technologies in the European energy mix, new national and European policies are needed to make these businesses profitable, such as implementing contracts for difference mechanisms with minimum and maximum limits to ensure price stability and increasing financing for renewable energy that does not require to make agricultural land unavailable (such as floating plants).

Regarding the importance of public policies for the green transition, simply financing the investments through grants is not enough. In order to ensure that private operators should invest in the development of renewable energy production in offshore areas, it is necessary for the authorities to regulate this activity differently from onshore energy production. Regulations for this activity must ensure predictability over a long period of time, sufficient for the amortization of the investment, and must establish as clearly as possible both the functioning of the mechanisms for protecting companies and consumers, and the amount of taxes and royalties to be paid to the state. In addition to these policies, long-term strategies for the development of electricity transmission infrastructure for coastal areas are also needed, so that they aim to integrate production capacities with large power variations.

A good topic for future research may be to calculate the LCOE for combined offshore wind and PV farms on the Black Sea coast or any other place in Europe, as it is predictable that the values would be much lower compared to simple PV islands, as the region offers strong and constant winds which are favourable for wind turbines. It would also be very useful to calculate the LCOE for certain islands and compare it with that of the energy currently produced by conventional sources to see the difference between them and the impact on the final price.

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