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Assessment of Floating Solar Panels Potential for Electricity Generation in the Adriatic Sea

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Abstract: Solar energy helps achieve several Sustainable Development Goals that have been proposed by the United Nations. Offshore solar energy deployment has not gained satisfactory attention when it comes to the Adriatic Sea. In this paper, the energy production, reduction of carbon dioxide emissions, and carbon credit of offshore solar power plant are estimated. The best location for a solar power plant in the Croatian part of the Adriatic Sea was selected considering solar potential, distance from shipping routes, proximity of existing onshore power grid, and visibility impact. The conceptual design of an offshore solar power plant was proposed. The obtained theoretical results show that offshore solar plant could annually produce 785 kWh of energy while avoiding 162 tons of carbon dioxide emissions. The floating solar panels could annualy earn a carbon credit of 10,342 €. The findings of this research could serve policymakers for the creation of a future solar power generation policy and future pilot experimental investigations in Croatia.

Keywords: CO_2 emissions, Floating PV, Solar power plant, SDG, Solar energy.

1. Introduction

Solar energy helps achieve SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation and Infrastructure). Solar energy is forecasted to be the leading renewable due to its potential to fulfill the global energy demand and the recent decline in the associated technology costs [1]. Offshore solar energy is an important element in reaching Europe's decarbonization objective. The energy produced from floating solar panels is one of the most promising and fastest-growing renewable energy. The growth trend of the cumulative global installed capacity of floating solar panels in MW is shown in Figure 1. Global floating solar panels deployment reached a cumulative global capacity of 3.8 GW in 2021. The solar panels market will continue to grow to help meet ambitious climate goals. The world's largest offshore solar plants are located in China, Japan, and the Republic of Korea [2]. In 2022, the largest floating solar plant with a capacity of 320 MW was installed in China. The floating solar panels can be installed in lakes, dams, ponds, rivers, seas and oceans. The components of a floating solar system are solar panels to harvest the solar energy, a floating buoyant structure to support, an anchoring and mooring system to position and help avoid excessive movement of the system, and electrical components for energy transformation and transportation. The floating solar systems help preserve land areas.

Compared to land-based solar panels, floating solar panels have higher efficiency due to the water-cooling effect, light reflection from the water, and less dust deposition [4], [5]. Furthermore, shading losses are minimized due to the open nature of sea surfaces. Floating solar panels reduce water evaporation and excessive algae growth [5], [6]. Problems with installing floating solar panels in offshore locations are saltwater corrosion and harsh wave and wind loads [7]. The studies showed that numerous benefits can be provided by the integration of floating solar plants with other RES technologies [8]. A combination of offshore wind and solar energy has proven to be an effective approach to mitigating the intermittency in energy supply.

Figure 1. Growth trend of cumulative global installed capacity (MW) of floating solar systems [3]

In the Croatian part of the Adriatic Sea, there is not a single offshore renewable energy power plant. The Republic of Croatia is dependent on energy imports, while a large share of the primary energy consumption mix has oil (20.4%) and natural gas (9.6%). Hydropower plants with the largest share (47.5%) are the prevailing renewable sources of electricity [9]. Although the country has significant solar energy potential, only 1% of electricity comes from onsite solar power plants. In 2023, with 238.7 MW of added installed solar Croatia's total installed solar capacity now stands at 462.5 MW. In 2024, solar power capacity reached 463 GW or 9%. Hydropower generation depends on the availability of water and is therefore highly affected by the impacts of climate change. Therefore, it is necessary to increase the deployment of other renewable sources in Croatia. The study [10] identified more than 290,00 km² of offshore area available for offshore wind and solar power plants. Although Croatia has significant offshore solar and wind energy potential, it needs a specific regulatory framework for these technologies and national strategic policies. The use of renewable energy in Croatia become an important issue as the country becomes increasingly dependent on fossil fuel imports. Previous studies investigated offshore wind energy exploitation in Croatia, while the exploitation of offshore solar energy isn't explored. This paper aims to analyze potential energy production from solar power plant in the Croatian part of the Adriatic Sea. Furthermore, the contribution to a reduction of carbon dioxide emission and potential carbon credit were estimated.

2. Methodology

The methodology used to estimate the energy potential, reduced carbon dioxide emissions, and carbon credit of the solar power plant is presented in Figure 2. The best location of the solar power plant was selected considering solar resource potential and exclusion criteria. Moreover, the conceptual design of solar power is also presented along with the selection of commercial solar panels to be installed.

Figure 2. The workflow of this reserach

2.1. Solar Potential

The Republic of Croatia has a warm temperate Mediterranean climate (Csa), according to the Köppen-Geiger climate classification. Climate of northern and northeastern areas have a warm temperate humid climate (Cfa). The Adriatic coast enjoys a Mediterranean climate of hot, dry summers and cool, rainy winters. The Adriatic

Sea is a semi-enclosed sea bordered by the Republic of Croatia on the east. The area under investigation is the Exclusive Economic Zone (EEZ) of Croatia. The Croatian part of the sea occupies an area of 31,479 km^2, with the coastline 6,278 km long [11]. To identify the region with the highest solar resource potential i.e. global horizontal irradiation the Global Solar Atlas [12] was used. Croatia is a good candidate for the exploitation of solar energy due to its Mediterranean, continental, moderately warm climate. The intensity of solar radiation in Croatia is among the most important ones in Europe. The sunniest parts of Croatia, receive about 40% more solar energy than Central Europe and 60% more than Northern Europe [11]. Croatia is aiming for a solar power capacity of 0.77 GW by 2030 [13]. A map of global horizontal irradiation for Croatia is shown in Figure 3. Croatia has between 2000 and 2,700 hours of sunshine a year and it is characterized by high irradiation from 1,300 kWh/m^2 in northern Croatia to 1,850 kWh/m^2 in southern Croatia. Solar irradiation is highest in July with values ranging from 7.43 kWh/m^2 to 5.89 kWh/m^2, while December is the month with the lowest values for solar irradiation, ranging from 0.62 kWh/m^2 to 1.50 kWh/m^2 [14]. Possible annual electricity generation by 1 kWp systems is from 975 kWh/kW in northern Croatia to 1,375 kWh/kW in southern Croatia [15]. Solar irradiation is the greatest on the open sea of the South Adriatic. An important aspect of using solar energy in Croatia is an increase in electricity consumption during summer months due to tourism. During the summer period, the global horizontal irradiation is up to five times higher compared to the winter months.

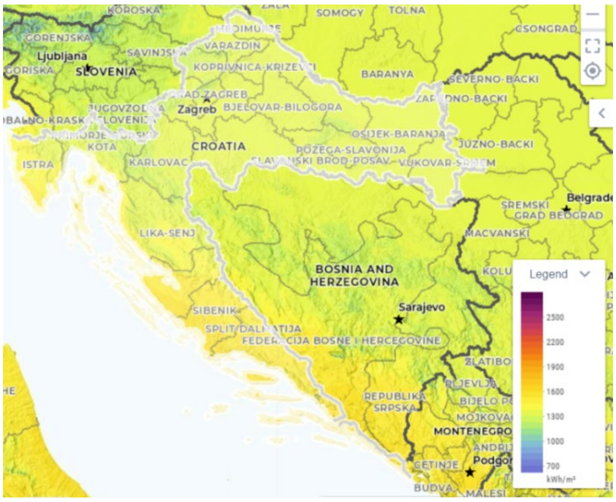

Figure 3. Global horizontal irradiation in Croatia [12]

2.2. Exclusion Criteria

Besides solar potential, the selection of an ideal location for a solar power plant should include several criteria such as shipping routes, environmental protected areas, military areas, distance from ports and airports, distance and capacity of existing electrical power grid, areas with high tectonic activity, etc. [16]. Two exclusion criteria were considered in this research:

- distance from shipping routes,
- proximity of onshore electrical power grid.

The offshore solar power plant should not be located near shipping routes. The buffer zone of 2 km from shipping routes was considered in this paper. The distance of offshore solar power plants to the onshore existing electrical grid determines the costs of cabling and other equipment. In the selection of an appropriate location for an offshore solar power plant, energy transmission needs to be considered. The distance from the electrical grid needs to be smallest to prevent high energy losses. Figure 4 shows a map of vessel density and electrical power grid in Croatia. The Adriatic Sea has high volumes of sea traffic. The currently available capacity can sustain small pilot projects. The onshore grid connection capacity needs to be significantly increased to support large-scale offshore projects. In the coastal part of Croatia, only the north-western region has additional grid connection capacity. There are three main lines of 110 kV cables on the coast: the first is laid along the main towns on the coast, the second one set down connecting islands of Krk, Cres, Mali Lošinj, and also Krk with Rab and Pag, and the third one laid along the islands of Brač, Hvar, Korčula, and Pelješac and further towards Dubrovnik [11].

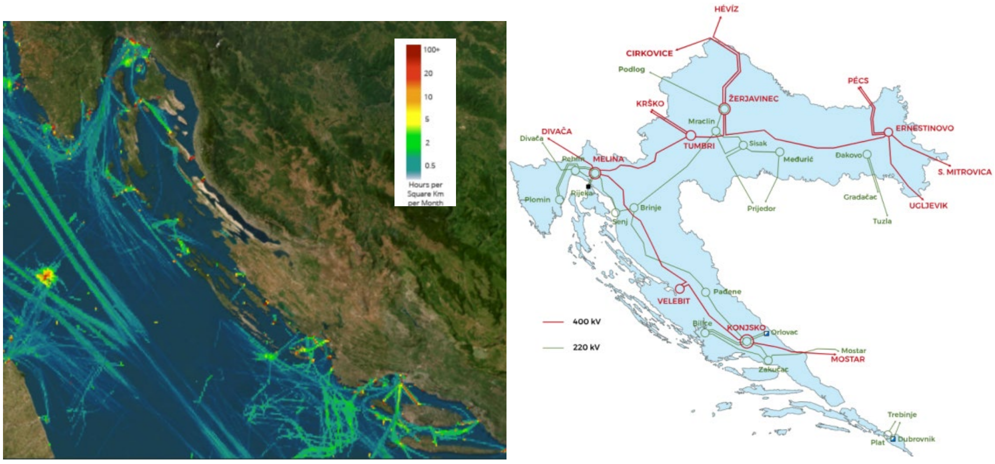

Figure 4. Ports and vessel density (left) [17], Croatian electrical power grid (right) [18]

2.3. Calculation of Energy Production and CO_2 Reduction

Croatia wants to cut its carbon dioxide emissions by 45% by 2030 and to abandon coal by 2033 [19]. Fossil carbon dioxide emissions in Croatia were above 17 million tons in 2022 [20]. To calculate the potential energy production of a solar power plant located in the selected location the following equation was used:

$$E = H \cdot A \cdot r \cdot PR \tag{1}$$

The data for monthly mean solar irradiation (H) were obtained from the PVGIS tool [21]. The open-source offshore solar data are not available, thus solar data for the onshore site closest to the selected location were used. The total solar panel area is A=3689 m^2 and the solar panel yield is r=0.18 while performance ratio is PR=0.75. Besides producing energy from renewable source, one of the benefits of offshore solar power plant is the contribution to the reduction of carbon dioxide emissions. The annual carbon dioxide emission that could be reduced was calculated using the following equation:

$$CO_2\ emissions = E \cdot EF \tag{2}$$

The emission factor of 0.206 tCO_2/MWh for the year 2023 was used according to [22]. Carbon credit that could be earned by the installation of solar power plant is calculated based on considering the carbon credit price of 63.96 €/t in the European market [23].

$$Carbon\ credit = CO_2\ emissions \cdot 63.96\ €/t \tag{3}$$

3. Results

3.1. Site Selection

Areas with high solar potential significantly influence the solar power plant efficiency and economic viability. Considering the solar potential, shipping routes, and the existing electrical grid, a location (43.60 lat., 15.88 long.) close to the towns of Šibenik and Primošten was selected for an offshore solar power plant as can be seen in Figure 5. The coast of Croatia has a large number of islands and high tourist activity during the summer period. Therefore, the visibility impact of solar power plant should be considered due to social acceptance. To avoid visual impact and ensure social acceptance the floating solar power plant is located 2 km from shore. The conceptual design of a solar power plant was proposed to calculate the occupied sea area.

Figure 5. Location for offshore solar power plant

3.2. Floater and Plant Design

The design of a floating platform for solar panels needs to minimize its footprint, influence the environment, and lower wave forces. For a conceptual design of solar power plants the patented flexible floating platform from the Norwegian company OceanSun [24] shown in Figure 6a) was selected. The composition of the OceanSun floating system is shown in Figure 6b). OceanSun's circular membrane uses buoyancy rings as floaters. The buoyancy rings are two airtight rings placed next to each other. This floating technology originated from the aquaculture industry. Membranes and mats are a type of floating technology that is generally made from rubber mats that act as a base for solar panel installation. The OceanSun platform can be used in rivers, lakes, and reservoirs, but also nearshore and offshore deployment. Logistics are significantly reduced compared to other floating solar systems. This type of platform was selected due to its ability to accommodate changes in the water level, and easy installation, and maintenance. This is a 1 mm thin flexible circular membrane with buoyancy rings made from HDPE with a 20-year lifetime in saltwater. The platform enables direct cooling of the solar panels (Figure 6c) increasing the power output by 10%, while CO_2 is reduced by 10% compared to other floating solutions [24].

a) b) c)

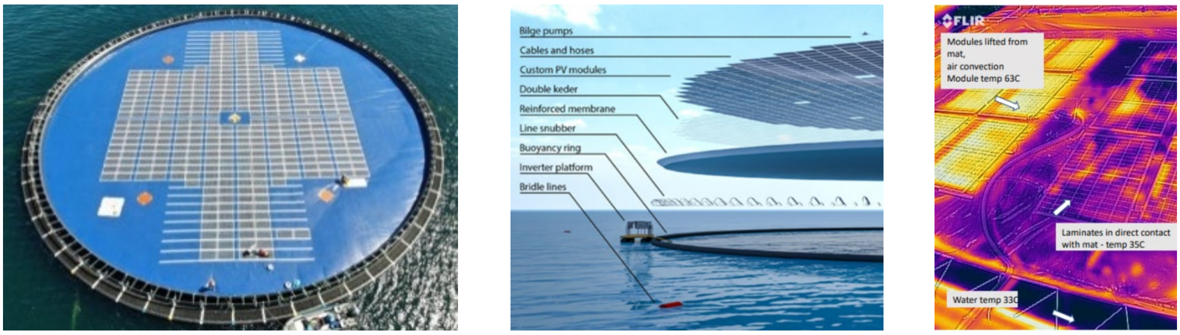

Figure 6. a) OceanSun platform, b) Elements of platform, c) Thermal image of platform [17]

The total weight of the platform is 55 tons including all panels, pumps, rings, and the membrane [24]. Several floating platforms could be placed in selected location with shared anchors and mooring system for larger power generation. This solution uses a minimum of materials to achieve the required buoyancy i.e. has a low Levelized Cost of Energy. Ocean Sun uses up to 65% less plastic, 90% less aluminum, and 50% less copper compared to other floating PV solutions [24]. The membrane allows the floating platform to move along with the waves, resulting in lower wave forces [25]. The hydro-elastic recyclable polymer floating membrane placed on a circular floater prevents waves from breaking and saltwater intrusion. Inverter stations could be placed on land or on barges next to the platform. The platform reduces water loss due to evaporation and mitigates underwater algae growth. OceanSun has operated several pilot and demonstration facilities in Europe and Asia. OceanAs Energy installed an innovative floating solar technology on the water reservoir of the Banja hydropower plants in Albania. This is the first floating PV project in Albania and the Western Balkan region. The plant with a total installed capacity of 500 kWp consists of four individual floating units, each unit has a surface area of approximately 4,000 m^2 and is equipped with 1,536 solar panels [26]. During sunny days, this floating solar power plant generated 3,644 kWh/day [27].

To determine the energy production of the solar power plant, solar panels Sunmodule Plus SW 300 [28] were selected. Figure 7 shows the dimensions of the solar panel. Table 1 shows the characteristics of the selected solar panel and their performance under standard test conditions. The platform used in this research has a diameter of 75 m, where 2,200 solar panels are placed in horizontal position. This arrangement allows the walkway between the rows of the solar panels to enable cleaning and maintenance of the modules. Solar panel occupies 1.68 m^2 of area and has a power generation of 300 watts at peak hours. The occupied sea area of a floating platform is 4,071 m^2, while the total area of solar panels is 3,696 m^2.

Table 1. Technical specification of the solar panel

Maximum power	300 Wp
Open circuit voltage	40.0 V
Maximum power point voltage	32.6 V
Short circuit current	9.83 A
Maximum power point current	9.31 A
Module efficiency	18%
PV technology	Monocrystalline PERC
Operating temperature	-40 to +85 °C
Cells per module	60
Dimension	1675x1001x33 mm
Weight	18 kg

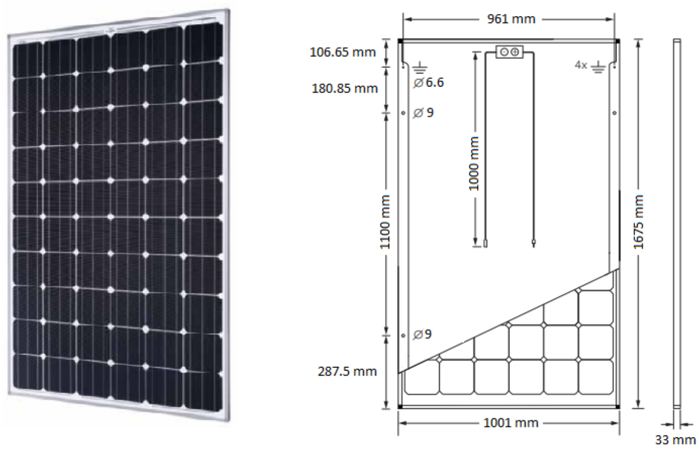

Figure 7. Solar panel Sunmodule Plus SW 300 [28]

3.3. Energy Production

The variation of monthly mean solar irradiation for selected location and estimated monthly energy production from offshore solar power plant are shown in Figure 8. The monthly mean solar irradiation is from 47 kWh/m^2 to 229 kWh/m^2. Solar radiation plays a key role in energy generation, which will be highest from May to August. The annual mean solar irradiation of the selected site is 132 kWh/m^2. The monthly mean energy production of solar power plant is from 31 kW to 152 kW. The annual mean energy production of solar power plant in selected location is 89 kW. The highest energy production could be obtained during the summer period (from June to August) while the lowest is during the winter period (from November to February). The high solar energy potential in the summer can help satisfy peak energy demand during the summer tourist season in Croatia. The obtained results show that offshore solar power plant could produce 785 MWh of energy annually while 19,625 MWh of energy during the 25-years power plant lifetime. The construction of offshore solar power plants can reduce the need for electricity imports in Croatia.

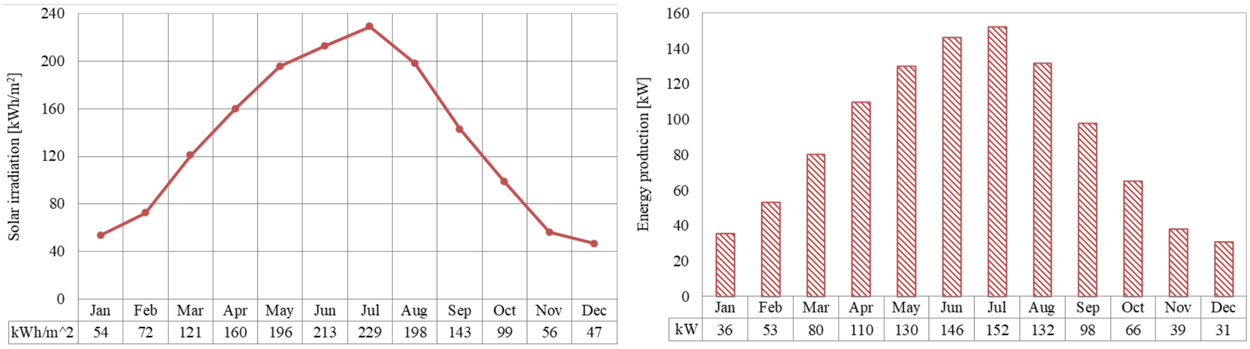

Figure 8. Mean solar irradiation (left), Mean energy production of offshore solar power plant (right)

3.4. CO_2 Reduction and Carbon Credit

Reduction of carbon dioxide emission and carbon credit for solar power plant is shown in Figure 9. Deployment of an offshore floating solar power plant in the selected location in the Adriatic Sea could annually reduce 162 tons of carbon dioxide emissions. The 10,342 € of carbon credit could be earned annually. Considering the 25-years lifetime of solar power plant, the total carbon dioxide emissions reduction is 4,050 tons and the potential carbon credit is 258,550 €. Croatia has not yet set a carbon dioxide removal (CDR) target. It should be emphasized that the price of carbon credit is expected to increase as well as carbon credit during the solar power plant lifetime.

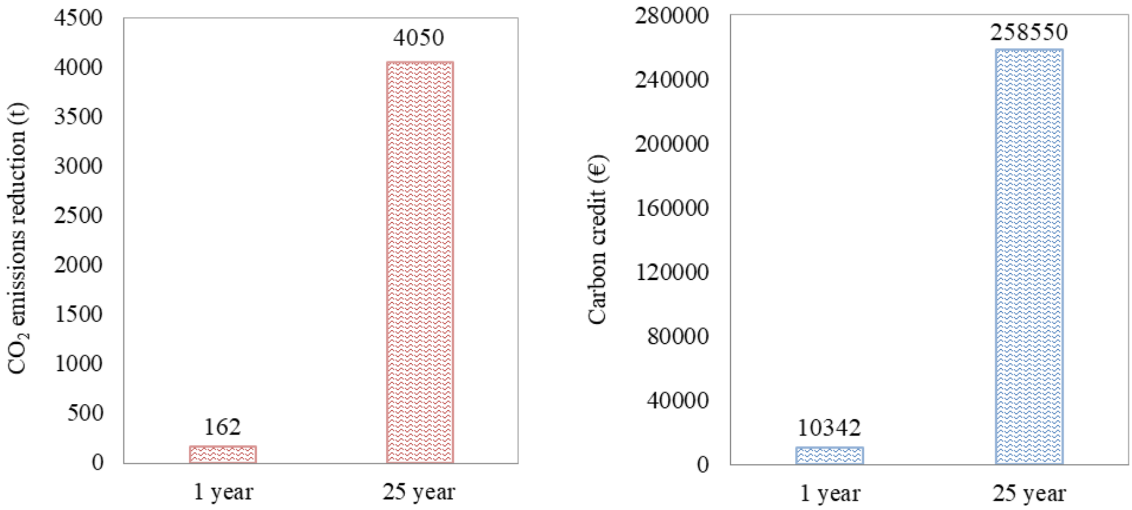

Figure 9. Reduction of carbon dioxide emissions (left), Carbon credit (right)

4. Conclusion

The land use limitation has raised interest in offshore solar energy worldwide. Croatia needs to decarbonize energy production and secure energy supply. Croatia has huge potential in using solar technology thanks to its geographical location and climate conditions. Therefore, this paper evaluates the energy production, reduction of carbon dioxide emissions, and carbon credit for an offshore solar power plant located in the Croatian part of the Adriatic Sea. The deployment of a solar power plant could annually produce 785 MWh of energy, avoid 162 tons of carbon dioxide emissions, and earn a carbon credit of 10,342 €. During the 25-years lifetime, solar power plant could produce 19,625 MWh of energy, reduce 4,050 tons of carbon dioxide emissions, and earn carbon credit of 258,550 €. Increasing offshore RES in Croatia can help the country achieve its decarbonization and climate goals as well as help the growth of the national economy. To harness this potential, Croatia will need to adopt various regulations in the field of offshore energy and increase the capacity of electricity grid. Future studies need to consider other exclusion criteria including environmental protected areas, water depth, fishing and military areas as well as the economic feasibility of offshore solar projects. Most studies from the literature are based on analytical and simulation analysis. Experimental studies are needed to investigate the in-site efficiency of solar power plants in terms of energy generation and environmental impact.

Nomenclature

Latin symbols

E	–	Energy production, in [MW].
H	–	Solar radiation, in [kWh m^{-2}].
A	–	Total solar panel area, in [m^2].
r	–	Solar panel yield or efficiency, in [%].
PR	–	Performance ratio.
CO_2	–	Carbon dioxide emissions, in [t].
EF	–	Emission factor, in [kgCO$_2$ kWh^{-1}].

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